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Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level

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Abstract

A common problem with Chinese district heating systems is that they supply more heat than the actual heat demand. The reason for this excess heat supply is the general failure to use control devices to adjust the indoor temperature and flow in the building heating systems in accordance with the actual heat demand. This results in 15–30% of the total supplied heat being lost. This paper proposes an integrated approach that aims to reduce the excess heat loss by introducing pre-set thermostatic radiator valves combined with automatic balancing valves. Those devices establish hydraulic balance, and stabilize indoor temperatures. The feasibility and the energy consumption reduction of this approach were verified by means of simulation and a field test. By moving the system from centrally planned heat delivery to demand-driven heat delivery, excess heat loss can be significantly reduced. Results show that once the hydraulic balance is achieved and indoor temperatures are controlled with this integrated approach, 17% heat savings and 42.8% pump electricity savings can be achieved. The energy savings will also have a positive environmental effect with seasonal reductions of 11kg CO_2, 0.1g SO_2, and 0.03g NO_x per heating square meter for a typical case in Harbin.

Key words: district heating, excess heat supply reduction, pre-set thermostatic radiator valves, automatic balancing valves, hydraulic balance, differential pressure control

1. Introduction

Research has shown that district heating (DH) is playing an important role in the societal goal of realizing an effective and sustainable energy system [1][2][3][4][5]. Along with the rapid growth of urbanization and industrialization, China has become one of the largest DH markets in the world in the last two decades. Statistics indicate that the total DH production in 2013 amounted to 3,197,032 TJ [6]. This number is still increasing steadily due to the process of rapid urbanization, expansion of the building area, enhancement of building services, and increases in comfort level. On the other hand, according to a World Bank report in 2012, the consumption of heating energy in China per square metre of floor area is almost twice that in developed countries at the same

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latitude. Nevertheless, the resulting room thermal comfort in China is still unsatisfactory [7]. Furthermore, the 2011 Annual Report on China Building Energy Efficiency [8] reports that 15% - 30% of the total heat is being lost due to excess heat supply in northern China's DH systems. These high losses are primarily due to a failure to use control devices to control the heating supply in accordance with the actual heating demand. There is an urgent need to apply appropriate technical approaches to improve the Chinese DH efficiency to create the maximum synergy between energy supply security and air pollution abatement, which are the two most important challenges for China today [9].

Chinese DH systems are very different from European DH systems. Structurally, a typical Chinese DH system is like this: pressurized hot water as the heat medium is produced in the central heat source and distributed to a few area substations (the primary side of the DH system). Each area substation then serves a number of multi-storey or high-rise buildings (the secondary side of the DH system). The heat entrance is the interface connecting the large-area substation to the building heating system (see Figure 1). It is usually equipped with shut-off valves, and measurement devices like thermometers, pressure gauges and heat meters, etc. [10].

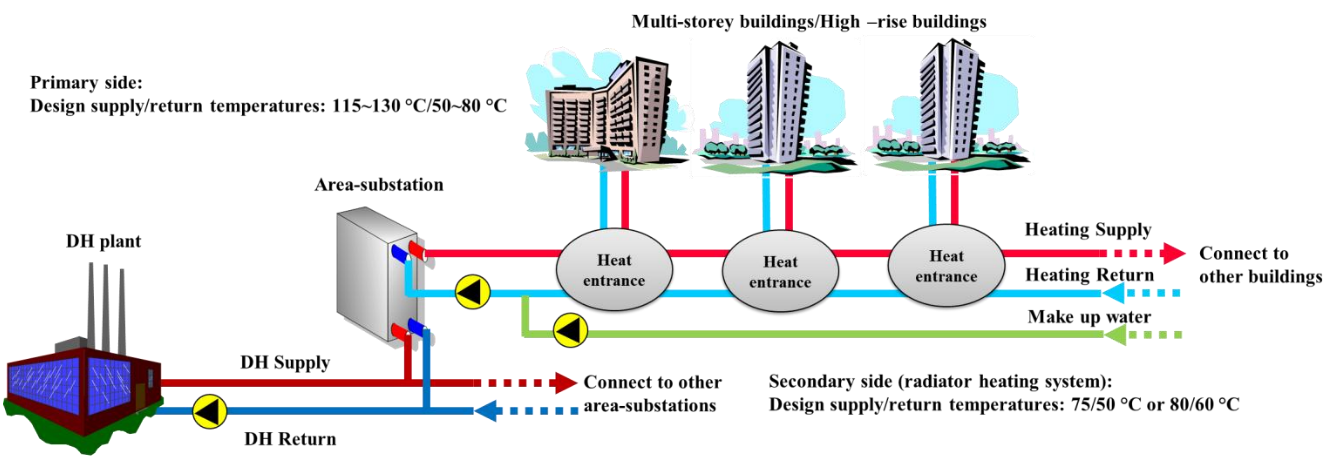

Figure 1. Typical district heating system used in China

In terms of temperatures, China's national design code [11] states that the DH primary side network should be designed with supply temperatures of 115 ºC~130 ºC and return temperatures of 50~80 ºC. The design code does not state any minimum design temperature difference. For the radiator space heating (SH) systems, the design supply/return temperatures are recommended as 75/50 ºC or 80/60 ºC [12]. In practice, DH systems generally operate with different temperatures based on various conditions for the particular DH systems.

In terms of heat sources, the main heating production facilities are the coal-fired boilers and Combined Heat and Power (CHP) plants. For instance, in 2013, 48% of DH came from coal-fired boilers, 42% CHP plants, 8% gas-fired boilers, and the remaining 2% came from scattered and individual heating facilities. Furthermore, coal is the dominant DH fuel in China [13]. Statistics show that 91% of the total energy supply to DH systems came from coal in 2008 [14].

Moreover, unlike European DH systems where DH supply covers both SH and Domestic Hot Water (DHW), approx. 90% of Chinese DH systems supply SH without DHW [15].

These important characteristics make it possible to understand why excess heat supply occurs in typical Chinese DH systems.

From the perspective of temperature control, room temperature regulation and control functions are not available in approx. 84% of the total heating area in China [16]. According to the national code [12], 18 °C is the standard room temperature for heat consumers in northern China to evaluate whether the heating effect is up to the required standard. The DH utility usually increases the secondary circulation flow rate until at least critical consumers attain this standard, which often result in the systems operating with large volume flow and small temperature differences between the supply and return streams. Moreover, once the heat demands of the critical consumers are fulfilled, the secondary flow rate often remains constant, with the varying SH demand being met by adjusting the secondary side supply temperature. Furthermore, there is a lack of automatic weather compensation control in some cases at substation level. Manual adjustment may be applied. e.g., tentatively adjusting the opening of the control valve installed on the primary side of the DH system, which is eventually reflected in changes in secondary supply temperatures. Such manual operation is based on the experience of past years and the level of complaints from critical users of the system, and the purpose of adjusting the supply temperature is to correlate the heat supply with the outdoor air temperature. Consequently, when the supply temperature to the SH system is higher than required, consumers will open windows to get comfortable indoor temperatures. In some cases, TRVs are installed in the DH systems. However, they are typically left fully open. Due to the fixed heating charges based on heating area, not actual heat consumption, there is no incentive for consumers to consciously reduce the TRV settings in an oversupply situation. They would generally regulate the indoor temperature by opening the windows. All these factors mean that consumers are either unable to control their room heating supply or lack motivation for energy conservation, which means excess heat supplied is wasted.

From the perspective of flow control in the secondary DH network and at building level, there are no automatic flow control devices, which results in an uneven flow distribution in the secondary-side DH network. Buildings close to the substation receive more flow than needed and become overheated, whereas buildings located in distal parts of the network receive less flow than required and are unable to fulfil their heating requirements. There is a lack of hydraulic balance inside the buildings. Specifically, the secondary side of Chinese DH systems generally operates on a constant flow and pressure basis. The pressure head at the pump is controlled to maintain constant differential pressure at area-substations. In addition, the constant flow operation principle makes the pumps run at constant speed. Although there are some variable-speed pumps, they are mainly used to correct the deviation between the design and operation conditions in terms of the pressure head and flow rate. Large volume flow leads therefore to higher than necessary electricity consumption in circulation pumps, small temperature differences, high return temperatures, and network heat losses.

In summary, it can be said that the general failure to use temperature and flow control devices in Chinese DH systems is the direct cause of excess heat loss, which subsequently compromises the efficiency of Chinese DH systems.

Studies have investigated how to improve the efficiency of Chinese DH systems by focusing on various DH elements [17][18][19][20][21][22][23][24][25][26][27][28]. With the heat reform in 2006 in China, 16% of the total heating area in China was given a heat metering retrofit [16] to install Thermostatic Radiator Valves (TRVs) by the year 2012. A lot of research has been carried out on TRV application in Chinese heating systems [29][30][31][32][33][34][35]. For instance, Xu et al. [33] investigated how hydraulic performance and energy consumption in individual apartments and the whole system were influenced when TRVs were regulated and when windows were opened. Xu et al. [34] developed a dynamic model and simulated the thermal and hydraulic behaviour of SH systems employing TRV-controlled radiators in multi-family buildings. Liu et al. [35] analysed the heat metering methods currently available in China and proposed a new method for metering the heat consumption of individual households in accordance with the accumulated on-time as well as the floor space of each household.

However, when we examine the previous research mentioned above, there is still a lack of expertise or knowledge on optimizing building heating systems by correctly using the flow control and temperature control functions of TRVs, including their inherent relationship with energy consumption reduction and indoor temperature improvement.

In this paper, an integrated approach has been developed and applied to a real project in northern China. The technical feasibility is shown and the advantages are quantified. This could give enhanced understanding and guidance for renovating future Chinese DH systems.

2. Methodology

The research objects in this study were the building heating systems. The central hypothesis of this study rests on the idea that the flow and temperature control functions of TRVs combined with differential pressure management can reduce the excess heat supply experienced in current Chinese DH systems while reducing their energy consumption. This idea is reflected in the research question: how large is the potential for reducing excess heat consumption by using temperature and flow control in the heating system of buildings?

Chinese energy statistics usually use the unit “metric tons of standard coal equivalent” (tce) because the primary energy source for DH systems in China is coal, and one tce equals 29.31 GJ. Burning 1 ton Chinese standard coal (29.3GJ/tce) releases about 2600 kg CO_2, 24 kg SO_2, and 7kg NO_x [36]. If the proposed controls were applied in Chinese DH systems, energy consumption reduction would be achieved which would have considerable positive environmental impacts due to the heavy reliance on coal as DH fuel in China.

To show the inter-relationship between excess heat supply, overheating of rooms, and the hydraulic imbalance, we analysed the data from two real cases, Case-Beijing-A and Case-Harbin, and proposed a technical approach to solve the excess heat supply.

We performed a two-step analysis. Firstly, a field test was made to demonstrate the technical feasibility of the approach. The field test was carried out in a high-rise building in Beijing (Case-Beijing-B), which is structurally similar to Case-Beijing-A. Secondly, simulations for scenarios analysis were carried out using building simulation software: IDA Indoor Climate and Energy [37]. The prototype of the building model is one of the multi-storey residential buildings in Case-

Harbin. The linear fit-to-metered secondary supply temperatures from Case-Harbin were used as input for the model to run the simulation. The flowchart shown in Figure 2 illustrates the integrated design approach in this paper.

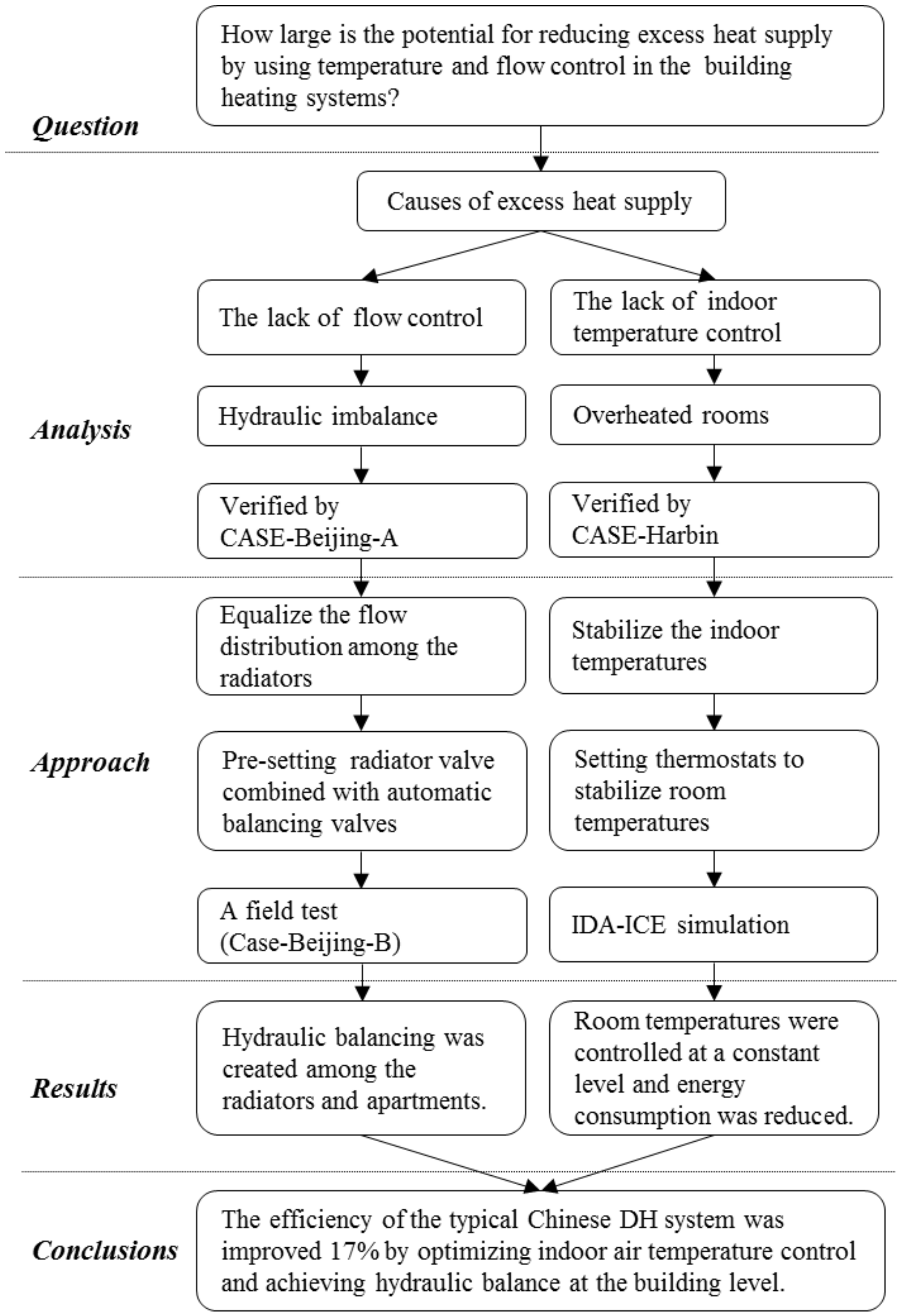

Figure 2. Flowchart of methods used in the study

2.1 Current situation from real cases

First, the data from two real cases were analysed to present the excess heat supply experienced in Chinese DH systems.

Case-Beijing-A refers to a DH system in Beijing. The data from a residential high-rise building heating system were used to indicate the link between hydraulic imbalance and excess heat supply. Case-Harbin refers to a DH system in Harbin. The data from the secondary side of one substation were obtained to verify the causal link between overheated rooms and excess heat loss.

2.1.1 Case-Beijing-A: Hydraulic imbalance and excess heat loss

To understand the hydraulic situation in high-rise building heating systems, the volume flow data from a 21-floor residential building in Case-Beijing-A were obtained. The DH water from an area substation flows into the building via the heat entrance, where manual balancing valves are used as the only flow control device to manage the flow distribution among the connected buildings. DH utilities usually use a flow index to determine the required volume flow of each building in accordance with the heating area served. The manual balancing valves are set at the beginning of the heating season according to the estimated flow and differential pressure across the controlled loop. After initial commissioning is finalized, the setting values of these manual balancing valves are kept for the whole heating season, except for minor adjustments.

In this high-rise building, each floor had the same heating area. The instantaneous volume flows per square metre along one of vertical supply risers were measured by using a hand-held ultrasonic flow meter. The volume flows along the risers were measured on the 1st, 6th, and 13th floors and on the 14th, 18th, and 20th floors, as shown in Figure 3. The results show how the volume flow per square metre decreased along the supply water direction.

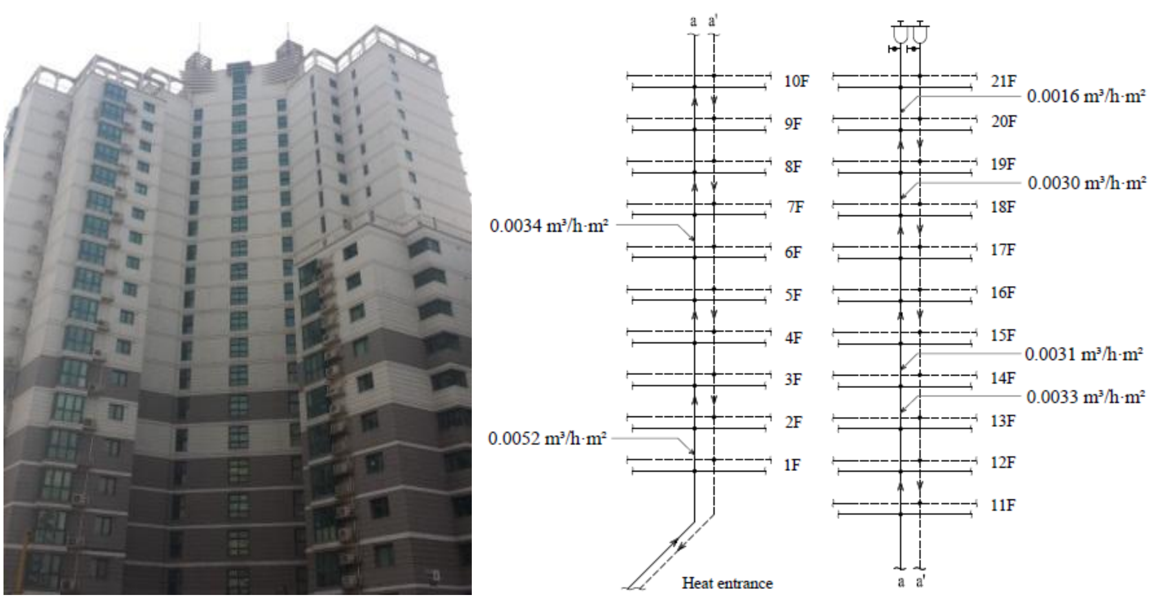

Figure 3. Flow measurement of a high-rise building in Beijing

The top floor should have a higher heat demand because of its larger exterior surface, but in reality, it was supplied with the least volume flow. Even though the volume flow per square metre on the top floor was less than 1/3rd that of the first floor, few thermal comfort complaints were reported. As a complaint over the phone is the most common way for Chinese heat consumers to inform the DH utilities about the heat effects, it can therefore be assumed that the floors below the top floor were receiving a higher volume flow than they actually required. These floors would be overheated. This case illustrates the excess heat supply caused by hydraulic imbalance in a building heating network where no flow control devices were used.

2.1.2 Case-Harbin: Overheated rooms and excess heat supply

To understand the relation between the overheated rooms and excess heat supply, the data from one of the area-substations of Case-Harbin were obtained. The data included the supply and return temperatures of the area substation and the corresponding outdoor temperatures. The data covered the entire heating period from 20 October 2013 to 20 April 2014. This area substation supplied heat to 14 multi-storey buildings with a heating area of 124,150 m^2.

The control situation in this case was that no indoor temperature control devices were applied in the SH system. In addition, automatic weather compensation control was not available at the substation, and the system was operating under constant flow rate. The secondary supply temperature was manually adjusted based on the average daily outdoor temperatures from metrological data and past years' experience in relation to the level of complaints from heat consumers.

The data presented in Figure 4 reveals the relationship between the supply temperature and outdoor air temperature being scattered when the manual control was applied. For the same outdoor temperature, the temperature differences between supply and return varied a lot. According to the records of the DH utility, very few complaints were received from the occupants during the heating period, and this implies that most consumers had room temperatures above 18 °C. This also implies that, for a given outdoor temperature, the lowest temperature difference has met the heat demand. All other temperature differences higher than the lowest values imply the buildings were overheated, since the constant flow principle was being applied in the secondary DH network. All heat supplied in excess of the lowest value can be regarded as heat loss due to excess heat supply. Due to the lack of the individual control for the indoor terminal heat units, overheated rooms inevitably leads to window opening, which also explains why several different temperature differences exist under the same outdoor temperature.

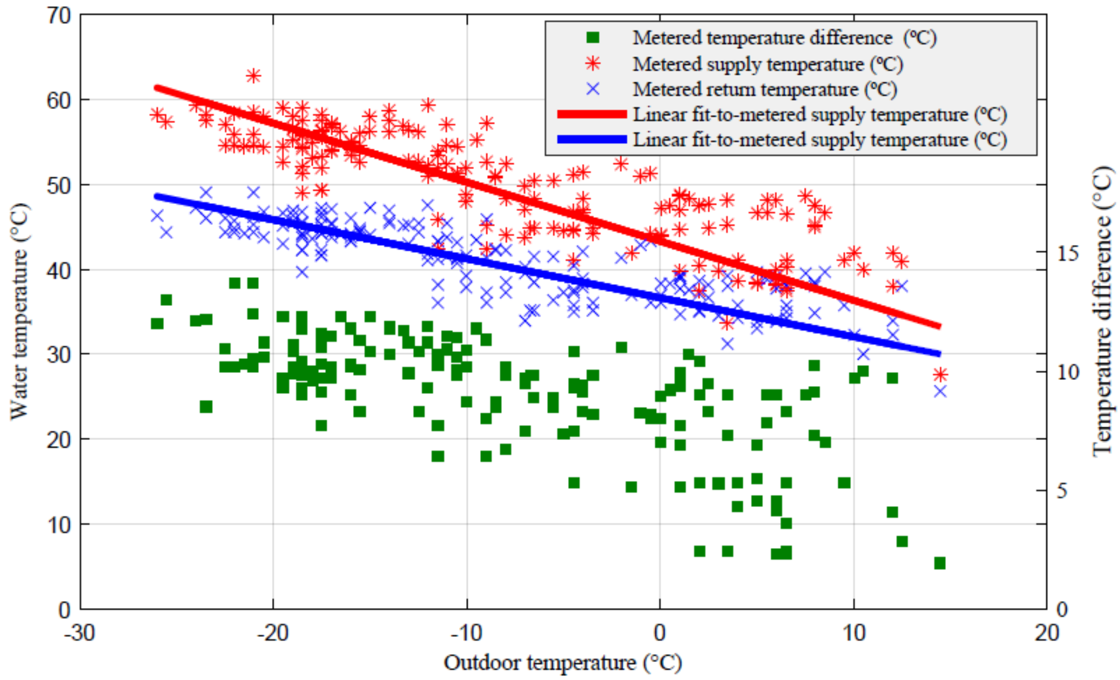

Figure 4. Supply and return temperatures of a substation in Case-Harbin during the 2013–2014 heating period

2.2 The proposed approach

To reduce the excess heat supply, an integrated approach was introduced that included the control devices: TRVs with pre-setting function, and automatic balancing valves. The SH systems considered in this paper are two-pipe radiator systems, and all the apartments have their own heating loops. A schematic configuration of the apartment heating loop applied in the integrated approach is illustrated in Figure 5. The number of the radiator might be different based on the particular apartment.

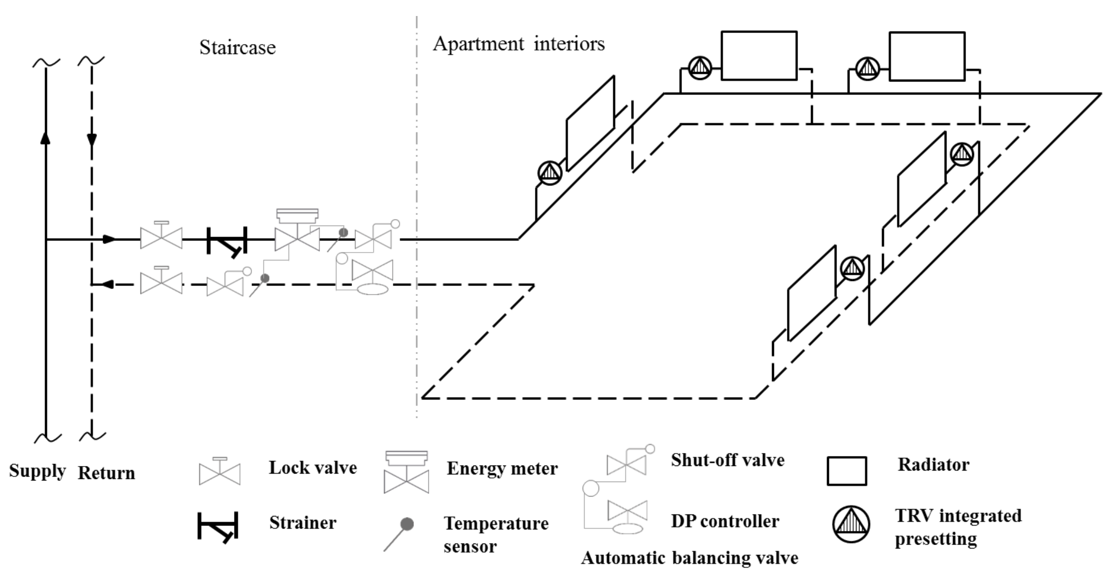

Figure 5. Schematic configuration of the apartment heating loop

TRVs consist of a thermostat and a radiator valve. The radiator valve is a flow control device. The degree of valve opening determines how much water flows through the valve into the radiator. This is controlled by the thermostat, which reacts to changes in room temperature.

The radiator valve with integrated pre-setting is a flow-limiting device that is fitted into the valve body to pre-set the maximum water flow through the radiator. The pre-setting values correspond to the scales marked on the radiator valve and the range is from 1 to 7 and N, which represent gradually increasing maximum flow limits [38], see Figure 6. The pre-setting values can be set in accordance with the requested design flow through the radiator and the pressure drop across the valve. To ensure the optimal regulation of the radiator valve and quiet operation, it is important to achieve the desired differential pressure across the valve. According to EN 215 [25], a differential pressure setting of 10 kPa is commonly used for radiator applications. Automatic balancing valves were therefore also applied in this approach to ensure the optimum operation of the radiator valve.

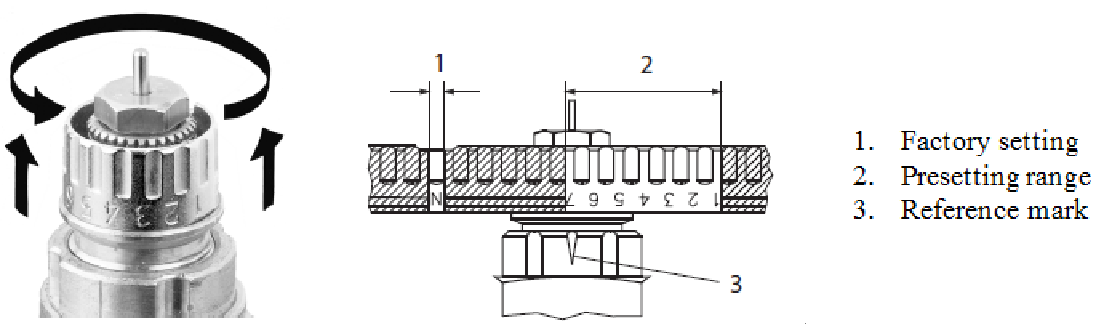

Figure 6. Pre-setting scales of radiator valve [38]

Automatic balancing valves consist of a self-acting differential pressure (DP) controller and an associated partner valve. The valves are linked to each other by a capillary tube. In this case, the partner valve was designed to shut off the pipe flow, and the DP controller was designed to maintain a constant differential pressure across a loop. The constant differential pressure across the controlled loop protects downstream control valves from excess pressures and offsets the effects of pressure variations caused by the movement of the control valves in other branches. By installing automatic balancing valves, all the controlled loops become pressure-independent zones [39]. This eliminates any problems caused by high or excess system pressures, including noise from the valves and poor control of room temperature.

Pre-setting radiator valves combined with automatic balancing valves equalize the flow distribution among the radiators and establish hydraulic balance at peak load. The thermostat function stabilizes the indoor temperature with regard to weather variations and free heat gains. By moving the system from centrally planned heat delivery to demand-driven heat delivery, the excess heat supply can be reduced, which can consequently reduce the energy consumption of Chinese DH systems and lead to positive environmental impacts.

2.3 Verification of the proposed approach

The technical feasibility of this approach and the improvements in indoor temperature control were verified by means of a field test (Case-Beijing-B) and building simulation software IDA Indoor Climate and Energy (IDA-ICE) 4.6.2 [37].

2.3.1 Field test in Beijing for flow control

The basic idea of the field test was to examine the flow control effect of using the radiator valve in combination with automatic balancing valves. With these two devices, the hydraulic balance is established and the flow distributed to each radiator can be controlled around the design value.

2. 3.1.1 Configuration of the field test

This field test (Case-Beijing-B) was carried out in a new 18-storey high-rise residential building in Beijing, which is structurally similar to Case-Beijing-A. The building's appearance is shown in

Figure 7 (left). The heating installation configuration for each apartment is illustrated in

Figure 7 (right). Details of the devices used are listed in Table 1. It should be mentioned that the radiator valves and the automatic balancing valves either need to be pre-set, or set during commissioning when the heating season starts, so that the radiators can achieve the required design flow under peak load. The set values of these two devices would be kept throughout the heating season or slightly adjusted if necessary. This field test focuses on the flow control effect of using these two devices, so the thermostats were removed for the experiment. In addition, automatic weather compensation control was applied at substation level for Case-Beijing-B to control the supply temperature, and variable speed pumps were available on the secondary-side of this DH system.

Table 1. Details of the relevant devices installed in tested apartment

Device name		Type	Dimension
Radiator valve		RA-N[21]	DN15 (mm)
Auto balancing valves	DP controller	ASV-PV[23]	DN20 (mm)
	Partner valve	ASV-M[23]	DN20 (mm)
Ultrasonic energy meter		SONOMETER 1100[24]	DN20 (mm)

The radiator valves were mounted on the radiator pipework. All the other devices mentioned above were installed in the staircase/hall (see

Figure 7 (right)), which was the location of the heat entry point for the apartment heating systems.

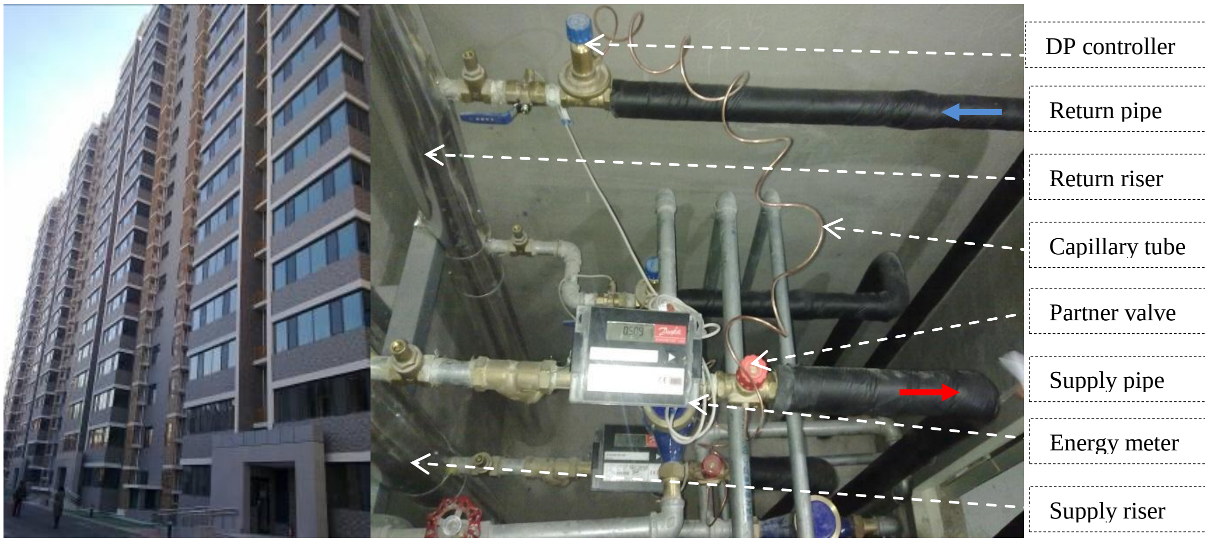

Figure 7. Real test case for the flow control approach

2. 3.1.2 Implementation of the field test

The field test consisted of two parts: Test I considered three apartments as test objects and focused on the pressure control function of the DP controller. Test II considered one apartment as the test object and focused on the flow limitation function of the radiator valve pre-setting function. Throughout the test, the other apartments' heating systems in this building were operating normally.

In Test I, three apartments with identical heating areas were chosen as the test objects. They were located on the right-hand side of the 2nd floor (201), the left-hand side of the 2nd floor (202), and the right-hand side of the 17th floor (1701). During the test, all the radiator valves were pre-set to N, i.e. the radiator valves were fully open.

The apartment loop flows were measured for apartments 201, 202, and 1701 when the DP controllers were in turn set at 5, 10, 15, 20, and 25 kPa. The ultrasonic energy meter of each apartment was used to measure the flow and investigate: 1) the hydraulic situation along the vertical pipe; 2) the flow changes in one apartment loop resulting from changing the set points of the DP controller at random or completely shutting off the loop flow of the other two apartments.

In Test II, one of the apartments was chosen as the test object. The aim of Test II was to investigate how the pre-setting function of the radiator valve controls the flow rate of the heating system. This apartment had five rooms with their own radiators and was located on the 2nd floor. Basic data about the apartment are given in Table 2. Each radiator was equipped with a radiator valve with pre-setting function. Test II was performed with the DP controller set at 10 kPa in accordance with EN 215 [25]. The design parameters of this heating system (supply/return/indoor temperature) were 75/60/18 °C. The design flow for each radiator could therefore be calculated and is given in Table 2. Based on the pressure drop of the heating loop and the design flow of the radiator, the pre-set scales of the radiator valve were determined and are listed in Table 2. The schematic configuration of the apartment-heating loop is illustrated in Figure 5. A Testo 925 [40] was used for measuring the indoor temperature.

Table 2. Basic information about the apartment tested

Room name	Floor area (m^2)	Heat load (W)	Desired operating temperature difference (°C)	Desired flow (l/h)	Pre-set values of the radiator valve
Living Room	18	810	15	46.4	3
Bedroom A	14.5	654	15	37.5	2.5
Bedroom B	8.7	391	15	22.5	1.5
Bathroom	3.4	168	15	9.6	1
Kitchen	4	180	15	10.3	1
Total	48.6	2203		126	

2.3.2 IDA-ICE simulation for indoor temperature control

For the indoor temperature control investigation, a simulation model of an eight-storey residential building was developed using IDA-ICE 4.2.6 [37]. To develop this building model, the building layout and building materials of one of the buildings in Case-Harbin were used. The building envelope properties and the thermal characteristics were as specified in China’s energy conservation design standard JGJ26-95 [41]. One of the apartments was modelled as a multi-zone model. Each room in the apartment was a separate zone. The room height was 2.7 m. This multi-zone model contained five heated zone areas: Bedroom N (north), Bathroom, Bedroom S (south), Kitchen, and Living Room, as well as three non-heated balconies and a non-heated staircase/hall (see *Figure 8*). The outdoor heating design temperature was -26 °C for Harbin and the indoor design room temperature was 18 °C. Based on the information, we run the multi-zone model equipped with ideal radiators, and obtained the peak heat load of each zone.

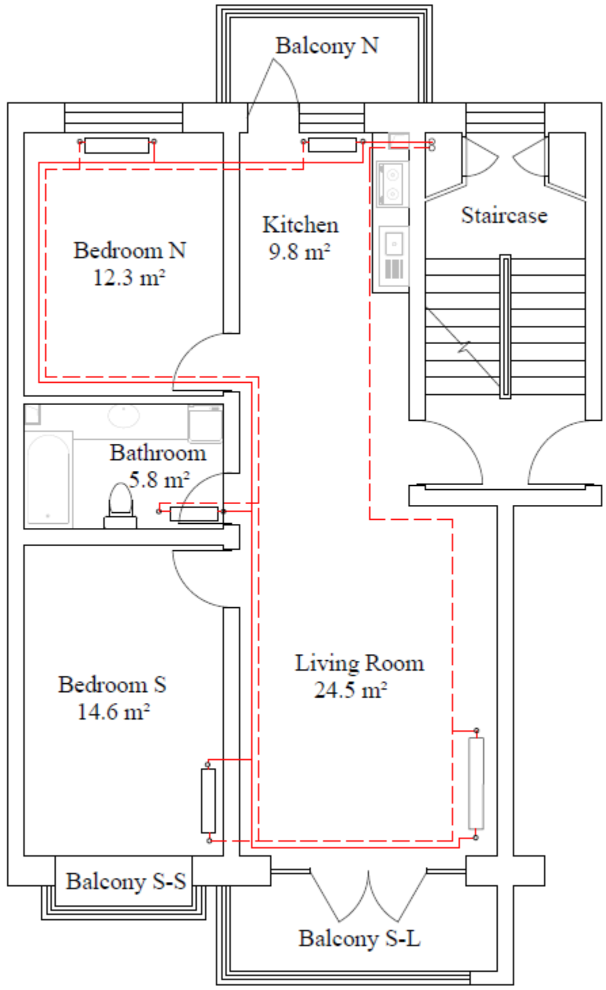

Figure 8. Multi-zone model

We dimensioned the radiators in accordance with Chinese standard [10]. In each zone, an M132-type radiator [42] was modelled as the room heating unit as in Case-Harbin. The design parameters of the SH system were the same as those for Case-Harbin: 80/60/18 °C (supply/return/indoor air temperatures). Correction factors were derived to correct for the actual output of each radiator. Accordingly, the maximum power of each radiator was determined, and the design flow limitation through the radiators and the design heat load for the SH system were defined.

Linear fit-to-metered supply temperatures were chosen in relationship to the outdoor temperatures shown in Figure 4. Here the secondary supply temperature is assumed to have been optimized by applying the weather compensation control at the substation and variable speed pumps in the secondary network of this system. To reflect the real conditions, an internal heat gain of 5.0 W/m^2 was considered [41]. Real weather data in Harbin city in 2014 was used to estimate the energy consumption for heating using EnergyPlus [43]. Two scenarios were considered: 1) without TRVs fitted to the radiators, which is the most common situation in Chinese SH systems; and 2) with TRVs fitted to the radiators to adjust the indoor temperature by setting the thermostat of the

TRVs. The room temperature of each zone, the energy consumption including heat consumption, and the electricity consumption of the pumps as well as the volume flow of the heating system were all compared based on the simulation results.

3. Results and Discussion

3.1 Field test in Beijing

3.1.1 Test I: Differential pressure control of the apartment heating loop

The test objects for Test I were three apartments 201, 202, and 1701.

The first aim of the investigation was to test whether the three test heating loops had the same distributed flow when the set points of the DP controllers were the same. The measurement results are shown in Figure 9. When the DP controllers of the three apartments loop were given the same set point (separately set at 5, 10, 15, 20, and 25 kPa), the three loops had a similar volume flow as expected. The deviation of the individual loop flow from the average flow of these three loops at the same set points was within ±15% (see Figure 9). This deviation can be considered as acceptable, because the set points of the DP controllers were adjusted by manually turning the spindle and there were no pressure gauges in the supply and return pipes to measure the pressure drop of the loops directly. Moreover, mechanical hysteresis influences the variations and causes a difference in the measured flow rates. The 2nd floor and 17th floor have identical floor heating areas, so theoretically the distributed flow could be the same. It can therefore be concluded that the hydraulic imbalance along the vertical riser was reduced after the installation of the DP controllers.

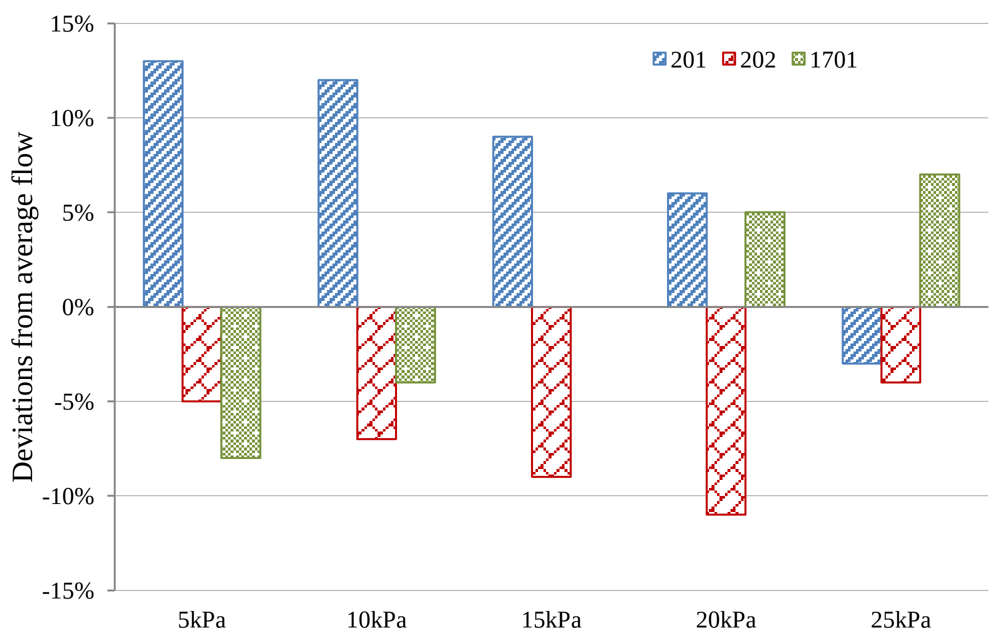

Figure 9. Deviations from the average flows of 201, 202, and 1701 at various set values of the DP controllers

The second aim of Test I was to test whether one of the heating loops was pressure-independent when the differential pressure of the other two heating loops changed. The results show that when the differential pressure of the other two tested heating loops was changed by adjusting the set points of the DP controllers or by completely shutting off the loops, the other apartments' heating systems kept operating normally and the flow of the third tested loop was not influenced or changed. This means that the automatic balancing valves were able to separate each heating loop as an independent pressure zone, and maintain the constant differential pressure in the controlled loop. It also implies that the DP controller controls the differential pressure across the controlled loop, which will ensure an optimal differential pressure across the downstream control valves. In this way, the flow within the controlled loop would not be affected by any system load changes, and noise would be avoided.

3.1.2 Test II: The pre-setting function of the radiator valves

For Test II, the test object was one apartment.

The apartment loop's mass flow, the supply and return temperatures, and the indoor temperature were measured with the set point of the DP controller at 10 kPa. The measurements were first carried out without radiator valves pre-set, and after that with them all pre-set. The mass flow measurement results (see Table 3) showed that after the radiator valves were pre-set, the total flow supplied to the apartment was reduced to 1/3, from 557l/h with no pre-setting to 181 l/h with pre-set. This implies that the flow rate through each radiator was limited dramatically by the pre-setting function. The flow rate in the case of pre-setting was close to the design flow rate of 126 l/h. This indicates that flow control by pre-setting the radiator valves on the terminal heat units is effective. The temperature measurement results showed that the temperature difference of the controlled loop increased by nearly 100% with the radiator valves pre-set, changing from 9 ºC to 17.3 ºC. Test II focused on the hydraulic control effect of pre-setting the radiator valves. The results clearly show that the large flow and small temperature difference problem which is typical in Chinese DH systems has been significantly relieved. This is the most important result that the test aimed to get. It also reflects the great energy-saving potential if the excess flow can be controlled.

In addition, at the start of the test, when there was no pre-setting of the radiator valves, the room temperature was 22.6 ºC (see Table 3), with heating power of 5.8 kW. The design capacity is 2.2 kW for -9 ºC outdoor air temperature. Due to lack of individual controls, the tenants regulate the room temperature by opening windows, which explains why the room temperature was no higher. After the pre-setting of the radiator valves, the delivered capacity was 3.6 kW and the room temperature went down to 22 ºC within two hours. A further decrease might be expected, but the 3.6 kW would be more than enough to sustain 18 ºC room temperature, seen in relation to the design capacity.

Table 3. Temperature measurement comparison between with and without pre-setting in Test II

Parameter of tested apartment loop	No pre-setting	Pre-setting
Total flow of apartment loop (l/h)	557	181
Supply temperature (°C)	62.6	62
Return temperature (°C)	53.6	44.7
Delta T (°C)	9	17.3

Average indoor temperature (°C)	22.6	22
Outdoor temperature (°C)	-4	-4

The field test showed that pre-setting radiator valves combined with the automatic balancing valves could control the loop flow close to the design level. Within the apartment loop, pre-setting the radiator valves limited the maximum flow of each radiator and created the right balance among the radiators. Flow limitation for each terminal heat unit prevented insufficient flow at distal units and excess flow at proximal ones. It reduces the total supplied flow and consequently the pump electricity consumption.

The differential pressure limitation of the automatic balancing valves provided the appropriate pressure drop over the radiator valves. The hydraulic imbalance along the vertical riser was reduced, and it guaranteed to set the thermostat properly to adjust the indoor temperature. At the same time, the noise from the radiator valves was avoided. Further adjustments of the room temperature towards the desired temperature could be achieved by adding a thermostat to the radiator valve, which would adjust the valve depending on the deviation from the set-point temperature of the TRVs.

In this field test, a dynamic hydraulic balance was created in the heating system by using pre-set radiator valves combined with automatic balancing valves. Every loop received the required flow and excess flow and insufficient flow were avoided. Every room received the required heat. Flow limitation improved the efficiency of the pump, and increased the temperature drop across the radiator. This field test indicates that the excess heat loss can be reduced through establishing dynamic hydraulic balancing in the building heating system.

3.2 IDA-ICE simulation

3.2.1 Model validation

The radiator heating system in the multi-zone model was designed in accordance with the Chinese design standard. The “linear fit-to-metered supply temperature” from CASE-Harbin (see Figure 4) defined the supply temperatures of the simulated heating system during the heating period. As shown in Figure 10 , the simulated return temperatures were compared with the linear fit-to-metered return temperatures from Case-Harbin. The results show that the deviation between the simulation results and the linear fit-to-return temperatures from Case-Harbin was on average about 2 ºC. It should be mentioned that the measurements from Case-Harbin were acquired at the area substation and were the average return temperatures from all the connected buildings. The deviation between the model outputs and the measured return temperatures were therefore considered to be acceptable and the model was considered valid.

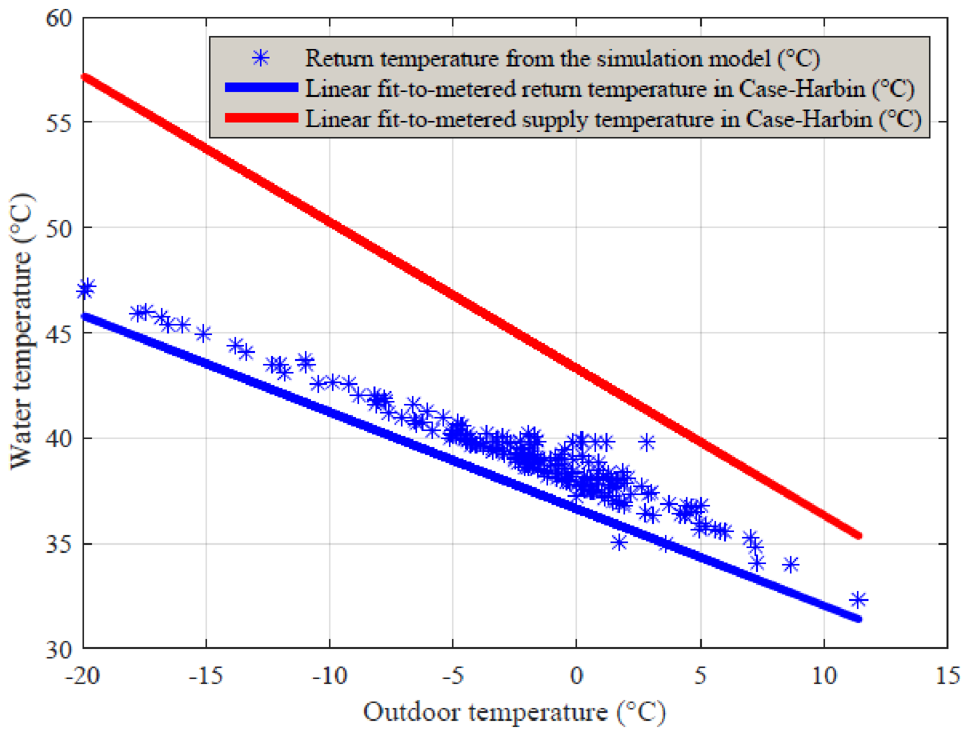

Figure 10. Supply and return temperatures for the model of the SH system

3.2.2 IDA-ICE simulation results

A simulation was carried out for the heating period in Harbin for two scenarios: radiators without TRVs and with TRVs. Several factors were considered in the simulation: room temperatures, heat consumption, pump electricity consumption, and the flow rate in the heating system.

Firstly, in terms of the room temperatures, the general results showed that without TRVs the room temperatures in all the zones were much higher than 18 ºC except for a few hours at the beginning of the heating period. The average room temperatures in all five zones over the entire heating period were around 22 ºC. With TRV control, the room temperatures in all the zones were constant at around 18 ºC. There are some minor deviations between the set temperature and the simulated room temperature, due to the 0.5 ºC proportional band (P-band). Because TRVs are proportional temperature controllers, they respond to any deviation from the set temperature by increasing or decreasing the flow into the radiators until the required room temperature is achieved. Figure 11shows the simulation results for two typical rooms in the multi-zone model: the northern room 'Bedroom N' and the largest room the 'Living Room', which reflects these small variations particularly clearly. The indoor air temperature can also be seen to have lagged a few days behind outdoor temperatures changes because of the thermal inertia of the building envelope materials.

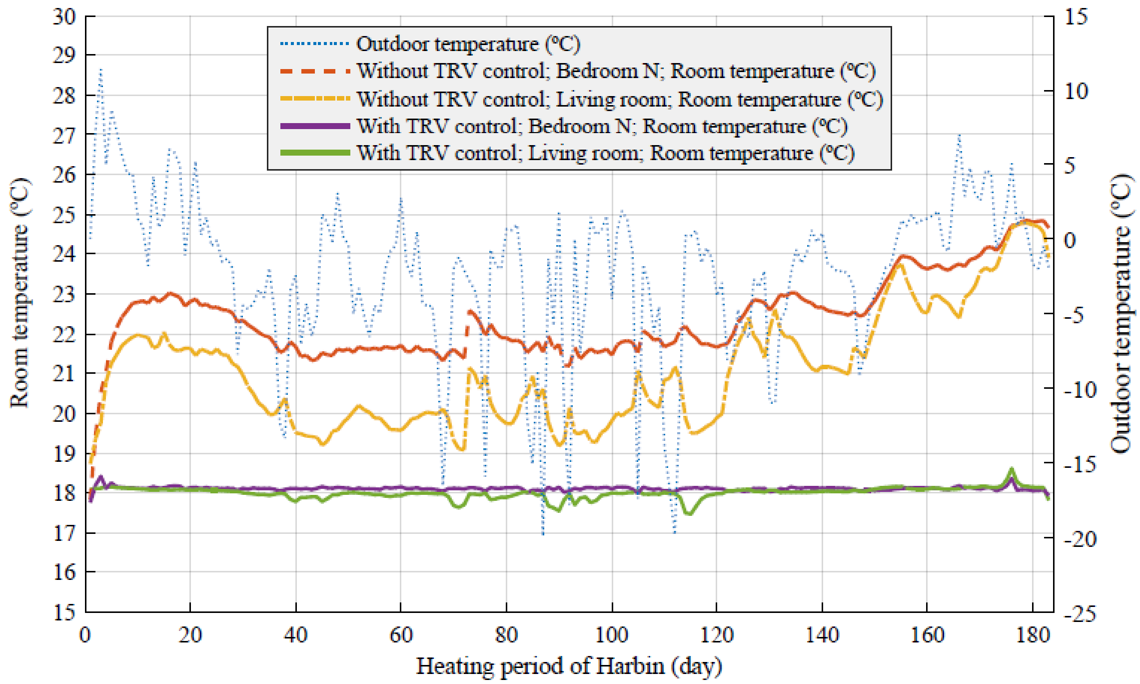

Figure 11. Zone room temperature of Bedroom N and the Living Room during the heating period

As shown in the simulation results, the application of TRVs provides the practical possibility for the room occupants to adjust the room temperature. When the rooms are overheated, the indoor temperature can be adjusted by setting the thermostat rather than opening the windows. Thermal comfort can imply multiple factors like indoor temperature, humidity, and draught [44]. But in the heating supply context, thermal comfort mainly refers to the indoor room temperature. In an unbalanced system, the thermal discomfort means excess heating for users close to the substation and insufficient heating for users far away from the substation. Through the implementation of the technical approach presented here, the indoor temperatures for rooms in different locations are balanced and close to the design room temperatures. We therefore conclude that the indoor thermal comfort is improved.

Correct use of TVRs has the potential to achieve great energy-saving effects. In some cases, heat consumers might not know how to use the TRVs correctly and might simply use the maximum set point, which will compromise the energy savings potential. The set points can be protected and locked by inserting the pins on the dial, and an energy-saving type of TRV can be used with a maximum set point of 20 ºC [45].

Secondly, the monthly heat consumption and pump electricity consumption were compared for the two scenarios, and the results are shown in Figure 12. Since the heating season is fixed in Harbin city and does not include May to September, no data were collected for those months. In terms of annual energy consumption, which was obtained by accumulating the monthly energy consumption over the heating season, the results imply that applying TRVs can reduce annual heat consumption by 17% and annual pump electricity consumption by 42.8% for this particular apartment. Here it should be noted that the pump energy consumption is very small compared to the heating energy consumption, only 0.1% of the heat energy delivered.

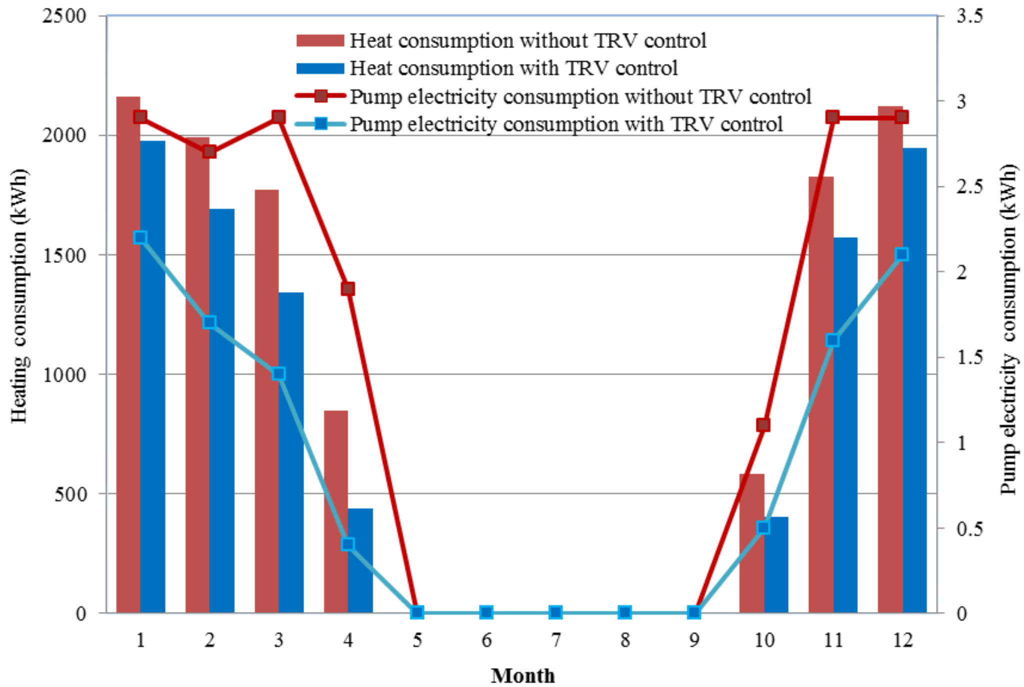

Figure 12. Heat consumption comparison between the scenarios with and without TRV control

Coal is the dominant DH fuel, and the dominant fuel for Chinese power plants. Burning coal is one of the main causes of air pollution in China [46]. Hydraulic balance can achieve 17% heat savings and 42.8% pump electricity savings. This will result in positive environmental impacts. In Case-Harbin, the total heating area in 2013-2014 heating season was 442,340 m^2. The measured seasonal heat consumption per m^2 was 0.7GJ/m^2, and the seasonal pump electricity consumption was 2.1 kWh/m^2. This reflects the currently unbalanced system situation. With hydraulic balance, the simulation results show that the seasonal heat consumption could be reduced by 0.12 GJ/m^2, and the seasonal pump electricity consumption could be reduced by 0.9kWh/m^2. The results imply that the total emission reduction for Case-Harbin could have been 4837 ton of CO_2, 44.7 tons of SO_2, and 13 tons of NO_x in the 2013-2014 heating season if hydraulic balance had been achieved. Therefore, the seasonal environmental impacts would reflect the reduction of 11kg CO_2, 0.1g SO_2, and 0.03g NO_x per heating square metre.

Moreover, with regard to the system's operation, it is important to note that applying TRVs changes the SH system from constant flow to variable flow (see Figure 13).

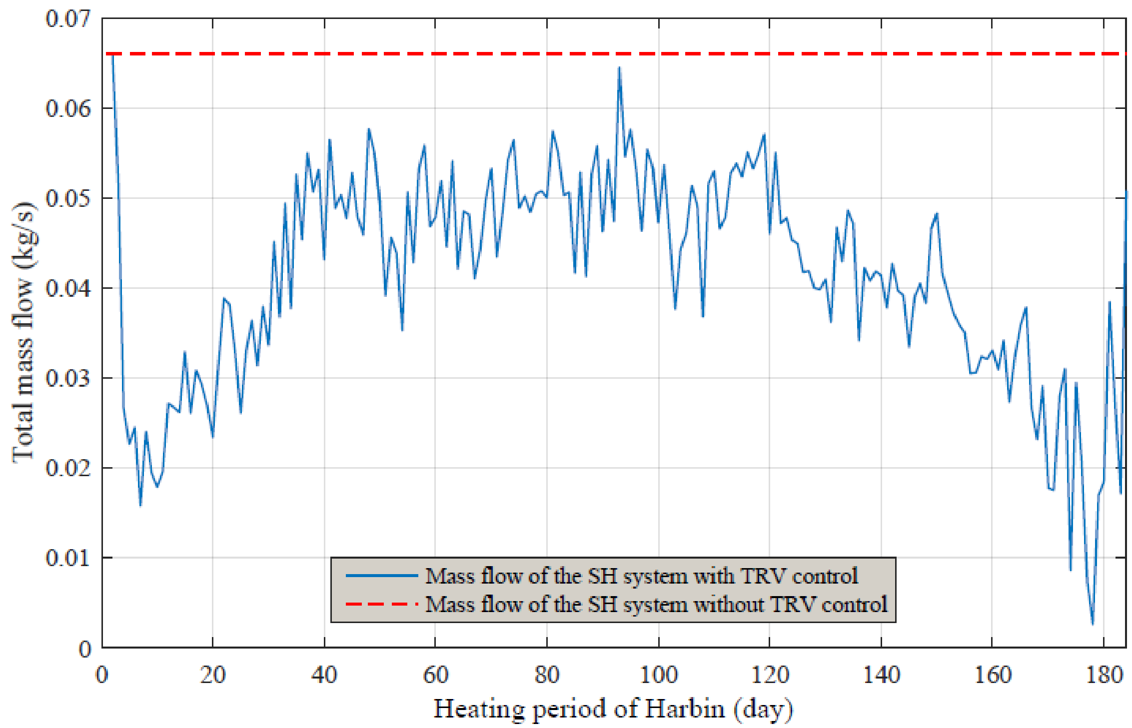

Figure 13. Total mass flow comparison between scenarios with and without TRV control

According to the results from the field test and the IDA-ICE simulation, the excess heat loss can be reduced by achieving hydraulic balance and optimizing indoor air temperature control at the building level.

In this study, the research object was the building heating system. Energy reduction at the building level will inevitably impact the whole DH system, reducing the amount of heat that area-substations have to deliver to a group of buildings and that the heat source plants have to deliver to the area-substations.

Dynamic hydraulic balancing ensures the apartment heating loops distribute the requested flow, with neither excess flow nor inadequate flow. Moreover, it means that the apartment heating loops are not influenced by each other if adjustments are made. Temperature control stabilizes the room temperature at comfort levels and avoids the room overheating. The integrated technical approach therefore reduces excess heat supply and excess heat loss. This means lower fuel consumption and less polluting emissions due to the fossil fuels heavily used in China. The economic benefits and environmental effects achieved will be considerable.

In the future, along with the energy consumption reduction in space heating systems, it is expected that Chinese DH systems will transition from the current centrally planned heat supply to demand-driven heat generation, which will also give increased comfort for users. In addition to this improvement in quality of life, DHW could also be integrated into DH systems to supply hot water in the future. This would be possible because the reduction in excess heat supply will result in large energy savings.

The high building density in Chinese' cities and the continuously expanding heating areas with rapid urbanization mean that there will be significant heat demands that need to be fulfilled. This emphasizes the significance of the kind of reductions in energy consumption in Chinese DH systems discussed in this paper.

4. Conclusions

To conclude, the proposed approach of combining the use of TRVs with an integrated pre-setting function and automatic balancing valves has been shown to be both feasible and effective in practice.

Firstly, a field test showed that pre-setting radiator valves combined with automatic balancing valves can establish dynamic hydraulic balance in a building heating system. Each controlled loop becomes an independent zone. The pre-setting of the radiator valve is an important function to equalize the flow distribution among the terminal heating units. Moreover, automatic balancing valves enable the radiator valves to work at optimum differential pressure level. As a result, the problems of excess flow and insufficient flow are avoided in the heating system. At the same time, the return temperature was decreased, and the temperature drop across the radiator was increased.

Secondly, IDA-ICE simulation results indicate that TRVs stabilize the room temperature. Wide use of TRVs in Chinese buildings can reduce heat consumption by 17% and pump electricity consumption by 42.8%, compared to a scenario without TRV control. In addition, adjusting TRVs transform the system from constant flow to variable flow. Variable speed pumps can be applied with variable flow rate. As coal is the dominant fuel for DH plants and power plants in China, the savings on both heat consumption and pump electricity consumption imply the positive environmental impacts.

Traditional Chinese DH systems seldom have control at the consumer end. By moving the control close to the end users, it is possible to bring the heating supply into line with the heating demand. The integrated assessment method and field test show that a well-balanced DH system can improve consumer thermal comfort and at the same time save significant pumping power. A well-balanced DH system allows heat users to pay less if the heating is charged on the basis of the real consumption. The heat users are satisfied also due to the improved room temperature control. At the same time, it would also be cost-effective for DH utilities, who could increase their profits by avoiding excess heat loss.

The developed integrated approach will help the decision makers and stakeholders to plan new or renovated district heating projects to be more energy efficient and cost effective. It would make a considerable contribution to energy supply security and air pollution abatement for Chinese society by giving smart control to district heating systems.

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Method for reducing excess heat supply experienced in typical Chinese district heating systems by achieving hydraulic balance and improving indoor air temperature control at the building level

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Abstract

A common problem with Chinese district heating systems is that they supply more heat than the actual heat demand. The reason for this excess heat supply is the general failure to use control devices to adjust the indoor temperature and flow in the building heating systems in accordance with the actual heat demand. This results in 15–30% of the total supplied heat being lost. This paper proposes an integrated approach that aims to reduce the excess heat loss by introducing pre-set thermostatic radiator valves combined with automatic balancing valves. Those devices establish hydraulic balance, and stabilize indoor temperatures. The feasibility and the energy consumption reduction of this approach were verified by means of simulation and a field test. By moving the system from centrally planned heat delivery to demand-driven heat delivery, excess heat loss can be significantly reduced. Results show that once the hydraulic balance is achieved and indoor temperatures are controlled with this integrated approach, 17% heat savings and 42.8% pump electricity savings can be achieved. The energy savings will also have a positive environmental effect with seasonal reductions of 11kg CO_2, 0.1g SO_2, and 0.03g NO_x per heating square meter for a typical case in Harbin.

Key words: district heating, excess heat supply reduction, pre-set thermostatic radiator valves, automatic balancing valves, hydraulic balance, differential pressure control

1. Introduction

Research has shown that district heating (DH) is playing an important role in the societal goal of realizing an effective and sustainable energy system [1][2][3][4][5]. Along with the rapid growth of urbanization and industrialization, China has become one of the largest DH markets in the world in the last two decades. Statistics indicate that the total DH production in 2013 amounted to 3,197,032 TJ [6]. This number is still increasing steadily due to the process of rapid urbanization, expansion of the building area, enhancement of building services, and increases in comfort level. On the other hand, according to a World Bank report in 2012, the consumption of heating energy in China per square metre of floor area is almost twice that in developed countries at the same

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latitude. Nevertheless, the resulting room thermal comfort in China is still unsatisfactory [7]. Furthermore, the 2011 Annual Report on China Building Energy Efficiency [8] reports that 15% - 30% of the total heat is being lost due to excess heat supply in northern China's DH systems. These high losses are primarily due to a failure to use control devices to control the heating supply in accordance with the actual heating demand. There is an urgent need to apply appropriate technical approaches to improve the Chinese DH efficiency to create the maximum synergy between energy supply security and air pollution abatement, which are the two most important challenges for China today [9].

Chinese DH systems are very different from European DH systems. Structurally, a typical Chinese DH system is like this: pressurized hot water as the heat medium is produced in the central heat source and distributed to a few area substations (the primary side of the DH system). Each area substation then serves a number of multi-storey or high-rise buildings (the secondary side of the DH system). The heat entrance is the interface connecting the large-area substation to the building heating system (see Figure 1). It is usually equipped with shut-off valves, and measurement devices like thermometers, pressure gauges and heat meters, etc. [10].

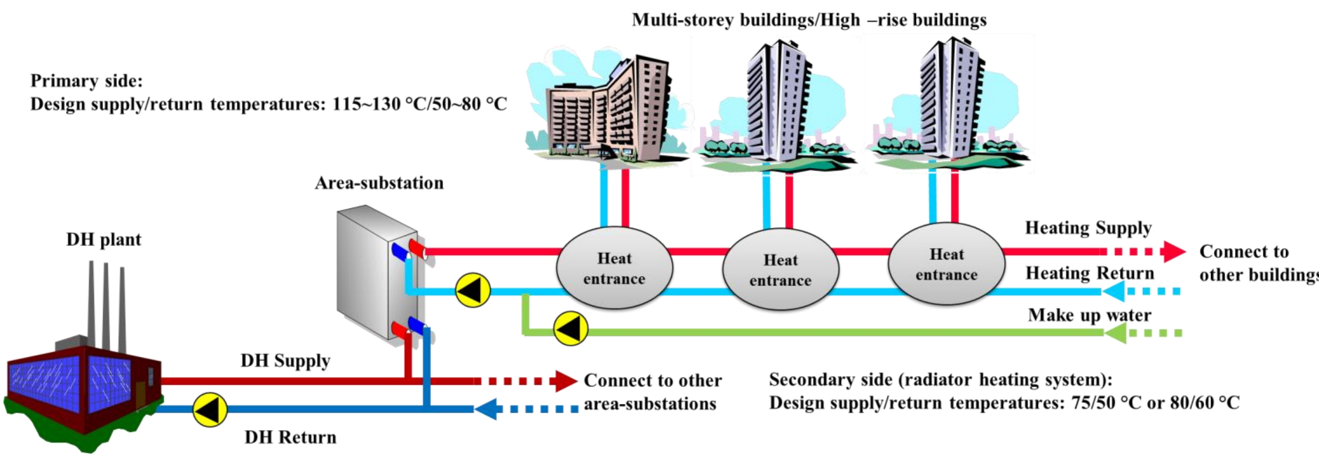

Figure 1. Typical district heating system used in China

In terms of temperatures, China's national design code [11] states that the DH primary side network should be designed with supply temperatures of 115 ºC~130 ºC and return temperatures of 50~80 ºC. The design code does not state any minimum design temperature difference. For the radiator space heating (SH) systems, the design supply/return temperatures are recommended as 75/50 ºC or 80/60 ºC [12]. In practice, DH systems generally operate with different temperatures based on various conditions for the particular DH systems.

In terms of heat sources, the main heating production facilities are the coal-fired boilers and Combined Heat and Power (CHP) plants. For instance, in 2013, 48% of DH came from coal-fired boilers, 42% CHP plants, 8% gas-fired boilers, and the remaining 2% came from scattered and individual heating facilities. Furthermore, coal is the dominant DH fuel in China [13]. Statistics show that 91% of the total energy supply to DH systems came from coal in 2008 [14].

Moreover, unlike European DH systems where DH supply covers both SH and Domestic Hot Water (DHW), approx. 90% of Chinese DH systems supply SH without DHW [15].

These important characteristics make it possible to understand why excess heat supply occurs in typical Chinese DH systems.

From the perspective of temperature control, room temperature regulation and control functions are not available in approx. 84% of the total heating area in China [16]. According to the national code [12], 18 °C is the standard room temperature for heat consumers in northern China to evaluate whether the heating effect is up to the required standard. The DH utility usually increases the secondary circulation flow rate until at least critical consumers attain this standard, which often result in the systems operating with large volume flow and small temperature differences between the supply and return streams. Moreover, once the heat demands of the critical consumers are fulfilled, the secondary flow rate often remains constant, with the varying SH demand being met by adjusting the secondary side supply temperature. Furthermore, there is a lack of automatic weather compensation control in some cases at substation level. Manual adjustment may be applied. e.g., tentatively adjusting the opening of the control valve installed on the primary side of the DH system, which is eventually reflected in changes in secondary supply temperatures. Such manual operation is based on the experience of past years and the level of complaints from critical users of the system, and the purpose of adjusting the supply temperature is to correlate the heat supply with the outdoor air temperature. Consequently, when the supply temperature to the SH system is higher than required, consumers will open windows to get comfortable indoor temperatures. In some cases, TRVs are installed in the DH systems. However, they are typically left fully open. Due to the fixed heating charges based on heating area, not actual heat consumption, there is no incentive for consumers to consciously reduce the TRV settings in an oversupply situation. They would generally regulate the indoor temperature by opening the windows. All these factors mean that consumers are either unable to control their room heating supply or lack motivation for energy conservation, which means excess heat supplied is wasted.

From the perspective of flow control in the secondary DH network and at building level, there are no automatic flow control devices, which results in an uneven flow distribution in the secondary-side DH network. Buildings close to the substation receive more flow than needed and become overheated, whereas buildings located in distal parts of the network receive less flow than required and are unable to fulfil their heating requirements. There is a lack of hydraulic balance inside the buildings. Specifically, the secondary side of Chinese DH systems generally operates on a constant flow and pressure basis. The pressure head at the pump is controlled to maintain constant differential pressure at area-substations. In addition, the constant flow operation principle makes the pumps run at constant speed. Although there are some variable-speed pumps, they are mainly used to correct the deviation between the design and operation conditions in terms of the pressure head and flow rate. Large volume flow leads therefore to higher than necessary electricity consumption in circulation pumps, small temperature differences, high return temperatures, and network heat losses.

In summary, it can be said that the general failure to use temperature and flow control devices in Chinese DH systems is the direct cause of excess heat loss, which subsequently compromises the efficiency of Chinese DH systems.

Studies have investigated how to improve the efficiency of Chinese DH systems by focusing on various DH elements [17][18][19][20][21][22][23][24][25][26][27][28]. With the heat reform in 2006 in China, 16% of the total heating area in China was given a heat metering retrofit [16] to install Thermostatic Radiator Valves (TRVs) by the year 2012. A lot of research has been carried out on TRV application in Chinese heating systems [29][30][31][32][33][34][35]. For instance, Xu et al. [33] investigated how hydraulic performance and energy consumption in individual apartments and the whole system were influenced when TRVs were regulated and when windows were opened. Xu et al. [34] developed a dynamic model and simulated the thermal and hydraulic behaviour of SH systems employing TRV-controlled radiators in multi-family buildings. Liu et al. [35] analysed the heat metering methods currently available in China and proposed a new method for metering the heat consumption of individual households in accordance with the accumulated on-time as well as the floor space of each household.

However, when we examine the previous research mentioned above, there is still a lack of expertise or knowledge on optimizing building heating systems by correctly using the flow control and temperature control functions of TRVs, including their inherent relationship with energy consumption reduction and indoor temperature improvement.

In this paper, an integrated approach has been developed and applied to a real project in northern China. The technical feasibility is shown and the advantages are quantified. This could give enhanced understanding and guidance for renovating future Chinese DH systems.

2. Methodology

The research objects in this study were the building heating systems. The central hypothesis of this study rests on the idea that the flow and temperature control functions of TRVs combined with differential pressure management can reduce the excess heat supply experienced in current Chinese DH systems while reducing their energy consumption. This idea is reflected in the research question: how large is the potential for reducing excess heat consumption by using temperature and flow control in the heating system of buildings?

Chinese energy statistics usually use the unit “metric tons of standard coal equivalent” (tce) because the primary energy source for DH systems in China is coal, and one tce equals 29.31 GJ. Burning 1 ton Chinese standard coal (29.3GJ/tce) releases about 2600 kg CO_2, 24 kg SO_2, and 7kg NO_x [36]. If the proposed controls were applied in Chinese DH systems, energy consumption reduction would be achieved which would have considerable positive environmental impacts due to the heavy reliance on coal as DH fuel in China.

To show the inter-relationship between excess heat supply, overheating of rooms, and the hydraulic imbalance, we analysed the data from two real cases, Case-Beijing-A and Case-Harbin, and proposed a technical approach to solve the excess heat supply.

We performed a two-step analysis. Firstly, a field test was made to demonstrate the technical feasibility of the approach. The field test was carried out in a high-rise building in Beijing (Case-Beijing-B), which is structurally similar to Case-Beijing-A. Secondly, simulations for scenarios analysis were carried out using building simulation software: IDA Indoor Climate and Energy [37]. The prototype of the building model is one of the multi-storey residential buildings in Case-

Harbin. The linear fit-to-metered secondary supply temperatures from Case-Harbin were used as input for the model to run the simulation. The flowchart shown in Figure 2 illustrates the integrated design approach in this paper.

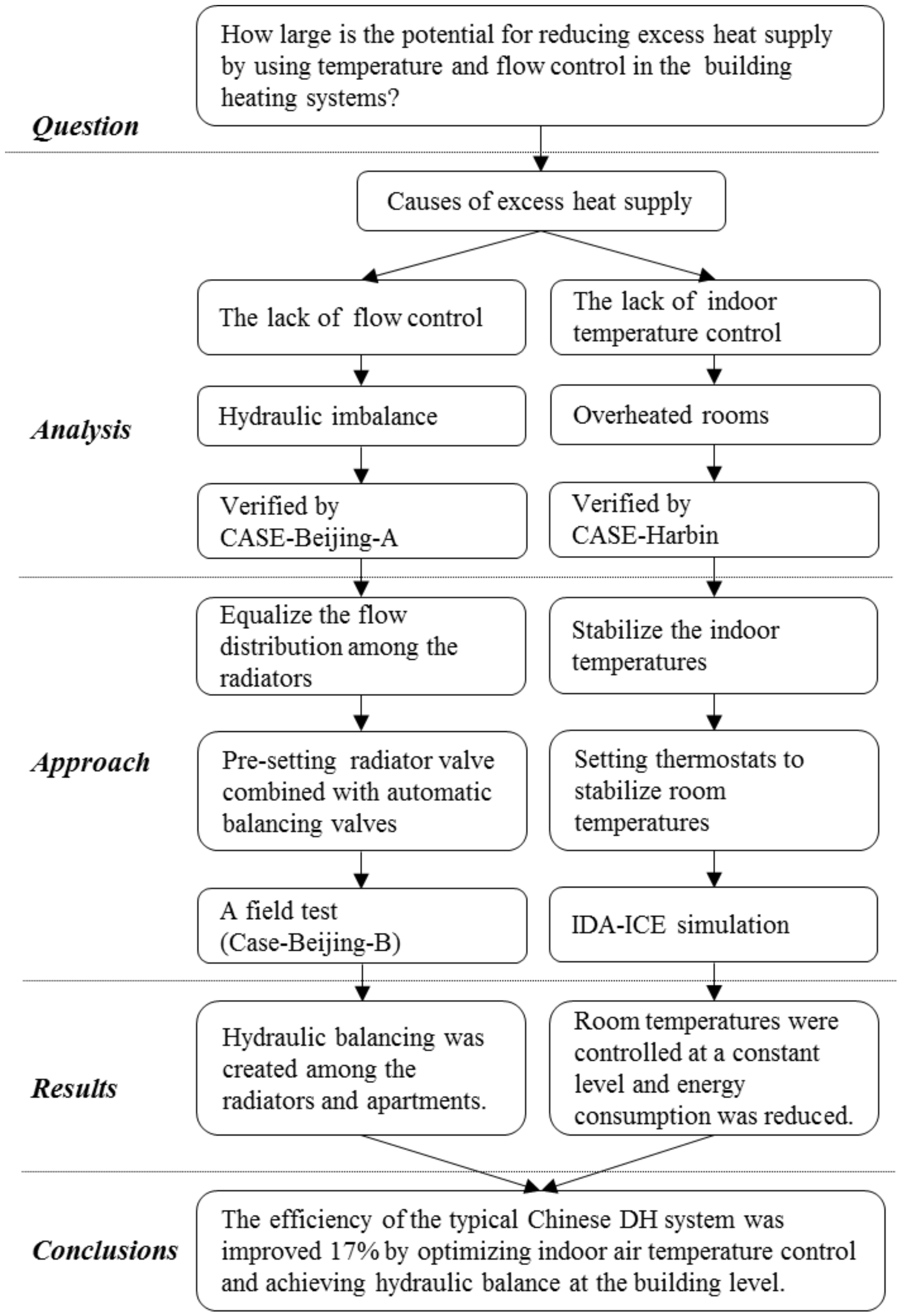

Figure 2. Flowchart of methods used in the study

2.1 Current situation from real cases

First, the data from two real cases were analysed to present the excess heat supply experienced in Chinese DH systems.

Case-Beijing-A refers to a DH system in Beijing. The data from a residential high-rise building heating system were used to indicate the link between hydraulic imbalance and excess heat supply. Case-Harbin refers to a DH system in Harbin. The data from the secondary side of one substation were obtained to verify the causal link between overheated rooms and excess heat loss.

2.1.1 Case-Beijing-A: Hydraulic imbalance and excess heat loss

To understand the hydraulic situation in high-rise building heating systems, the volume flow data from a 21-floor residential building in Case-Beijing-A were obtained. The DH water from an area substation flows into the building via the heat entrance, where manual balancing valves are used as the only flow control device to manage the flow distribution among the connected buildings. DH utilities usually use a flow index to determine the required volume flow of each building in accordance with the heating area served. The manual balancing valves are set at the beginning of the heating season according to the estimated flow and differential pressure across the controlled loop. After initial commissioning is finalized, the setting values of these manual balancing valves are kept for the whole heating season, except for minor adjustments.

In this high-rise building, each floor had the same heating area. The instantaneous volume flows per square metre along one of vertical supply risers were measured by using a hand-held ultrasonic flow meter. The volume flows along the risers were measured on the 1st, 6th, and 13th floors and on the 14th, 18th, and 20th floors, as shown in Figure 3. The results show how the volume flow per square metre decreased along the supply water direction.

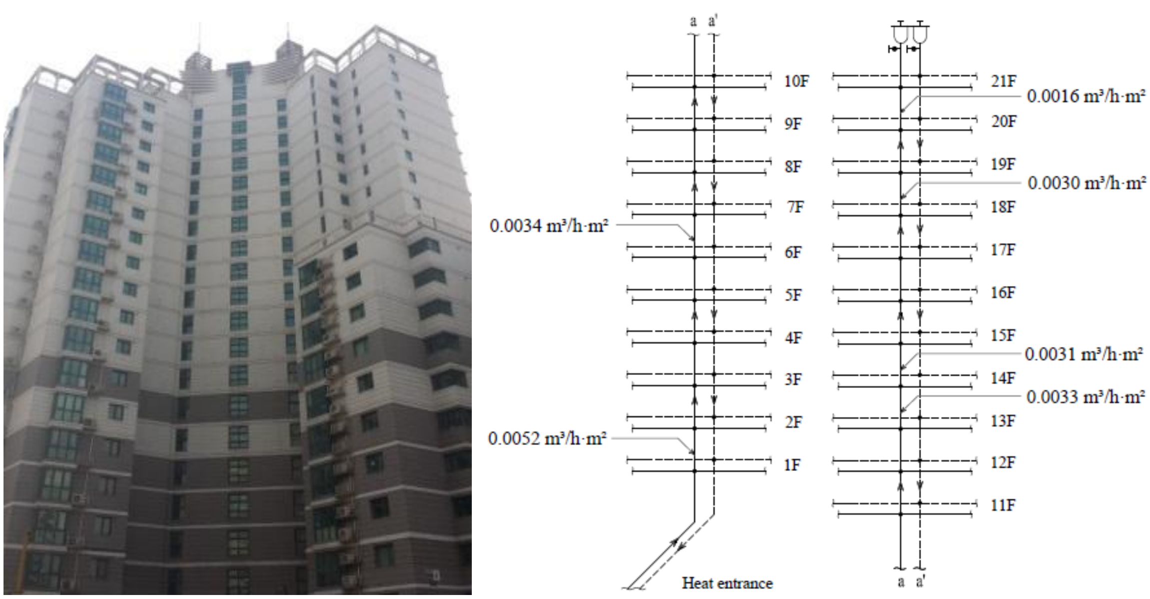

Figure 3. Flow measurement of a high-rise building in Beijing

The top floor should have a higher heat demand because of its larger exterior surface, but in reality, it was supplied with the least volume flow. Even though the volume flow per square metre on the top floor was less than 1/3rd that of the first floor, few thermal comfort complaints were reported. As a complaint over the phone is the most common way for Chinese heat consumers to inform the DH utilities about the heat effects, it can therefore be assumed that the floors below the top floor were receiving a higher volume flow than they actually required. These floors would be overheated. This case illustrates the excess heat supply caused by hydraulic imbalance in a building heating network where no flow control devices were used.

2.1.2 Case-Harbin: Overheated rooms and excess heat supply

To understand the relation between the overheated rooms and excess heat supply, the data from one of the area-substations of Case-Harbin were obtained. The data included the supply and return temperatures of the area substation and the corresponding outdoor temperatures. The data covered the entire heating period from 20 October 2013 to 20 April 2014. This area substation supplied heat to 14 multi-storey buildings with a heating area of 124,150 m^2.

The control situation in this case was that no indoor temperature control devices were applied in the SH system. In addition, automatic weather compensation control was not available at the substation, and the system was operating under constant flow rate. The secondary supply temperature was manually adjusted based on the average daily outdoor temperatures from metrological data and past years' experience in relation to the level of complaints from heat consumers.

The data presented in Figure 4 reveals the relationship between the supply temperature and outdoor air temperature being scattered when the manual control was applied. For the same outdoor temperature, the temperature differences between supply and return varied a lot. According to the records of the DH utility, very few complaints were received from the occupants during the heating period, and this implies that most consumers had room temperatures above 18 °C. This also implies that, for a given outdoor temperature, the lowest temperature difference has met the heat demand. All other temperature differences higher than the lowest values imply the buildings were overheated, since the constant flow principle was being applied in the secondary DH network. All heat supplied in excess of the lowest value can be regarded as heat loss due to excess heat supply. Due to the lack of the individual control for the indoor terminal heat units, overheated rooms inevitably leads to window opening, which also explains why several different temperature differences exist under the same outdoor temperature.

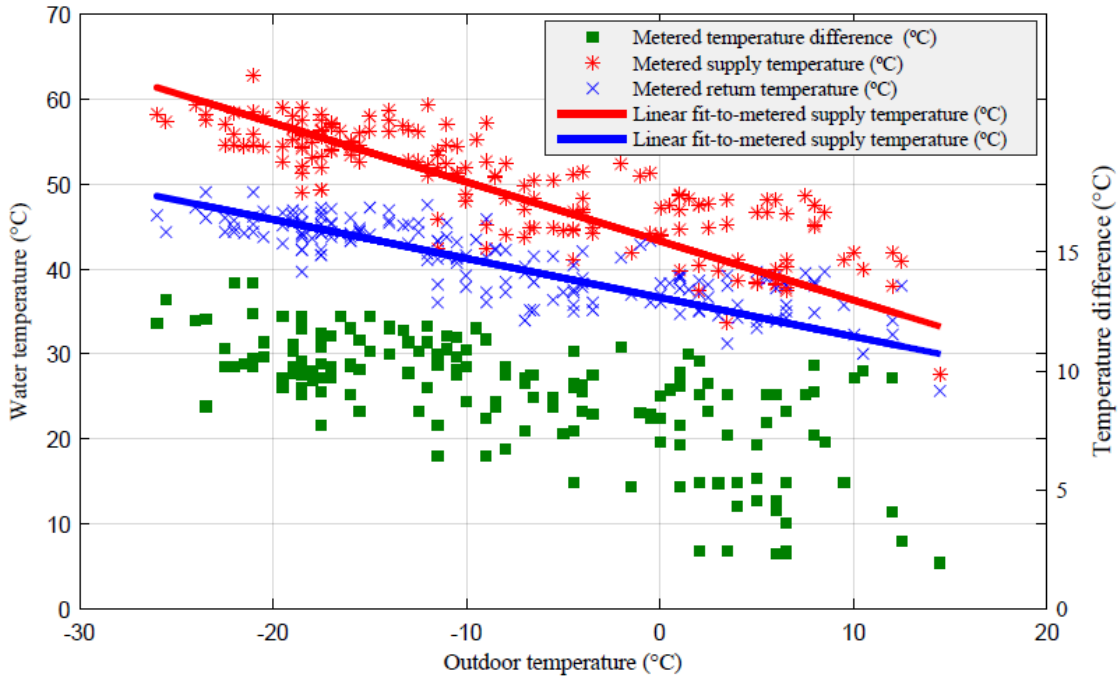

Figure 4. Supply and return temperatures of a substation in Case-Harbin during the 2013–2014 heating period

2.2 The proposed approach

To reduce the excess heat supply, an integrated approach was introduced that included the control devices: TRVs with pre-setting function, and automatic balancing valves. The SH systems considered in this paper are two-pipe radiator systems, and all the apartments have their own heating loops. A schematic configuration of the apartment heating loop applied in the integrated approach is illustrated in Figure 5. The number of the radiator might be different based on the particular apartment.

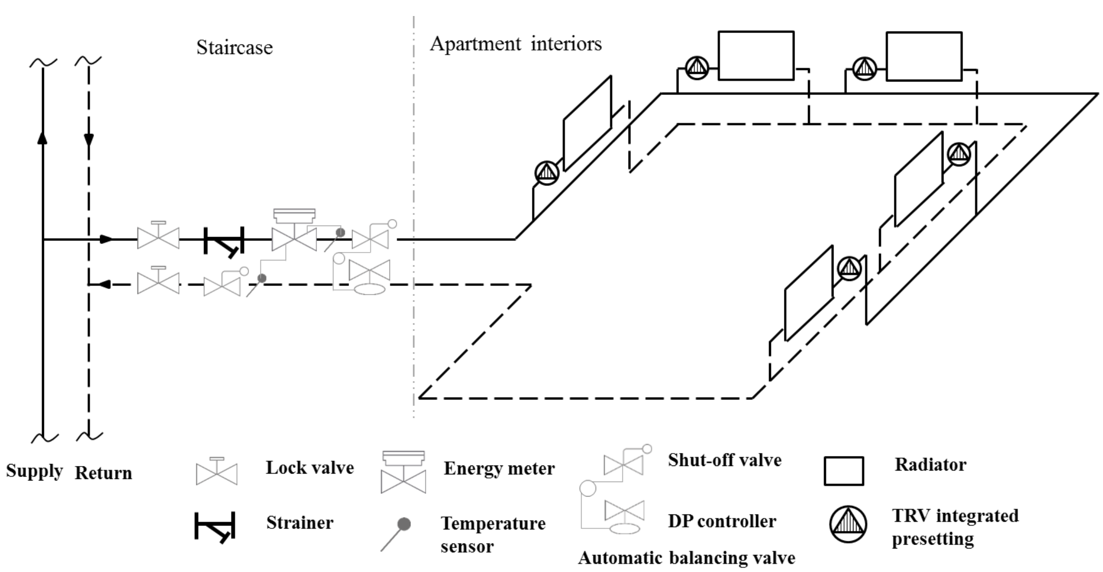

Figure 5. Schematic configuration of the apartment heating loop

TRVs consist of a thermostat and a radiator valve. The radiator valve is a flow control device. The degree of valve opening determines how much water flows through the valve into the radiator. This is controlled by the thermostat, which reacts to changes in room temperature.

The radiator valve with integrated pre-setting is a flow-limiting device that is fitted into the valve body to pre-set the maximum water flow through the radiator. The pre-setting values correspond to the scales marked on the radiator valve and the range is from 1 to 7 and N, which represent gradually increasing maximum flow limits [38], see Figure 6. The pre-setting values can be set in accordance with the requested design flow through the radiator and the pressure drop across the valve. To ensure the optimal regulation of the radiator valve and quiet operation, it is important to achieve the desired differential pressure across the valve. According to EN 215 [25], a differential pressure setting of 10 kPa is commonly used for radiator applications. Automatic balancing valves were therefore also applied in this approach to ensure the optimum operation of the radiator valve.

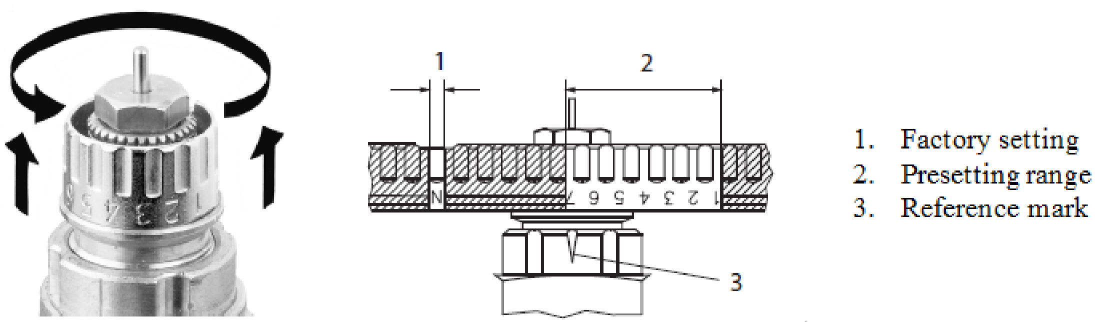

Figure 6. Pre-setting scales of radiator valve [38]

Automatic balancing valves consist of a self-acting differential pressure (DP) controller and an associated partner valve. The valves are linked to each other by a capillary tube. In this case, the partner valve was designed to shut off the pipe flow, and the DP controller was designed to maintain a constant differential pressure across a loop. The constant differential pressure across the controlled loop protects downstream control valves from excess pressures and offsets the effects of pressure variations caused by the movement of the control valves in other branches. By installing automatic balancing valves, all the controlled loops become pressure-independent zones [39]. This eliminates any problems caused by high or excess system pressures, including noise from the valves and poor control of room temperature.

Pre-setting radiator valves combined with automatic balancing valves equalize the flow distribution among the radiators and establish hydraulic balance at peak load. The thermostat function stabilizes the indoor temperature with regard to weather variations and free heat gains. By moving the system from centrally planned heat delivery to demand-driven heat delivery, the excess heat supply can be reduced, which can consequently reduce the energy consumption of Chinese DH systems and lead to positive environmental impacts.

2.3 Verification of the proposed approach

The technical feasibility of this approach and the improvements in indoor temperature control were verified by means of a field test (Case-Beijing-B) and building simulation software IDA Indoor Climate and Energy (IDA-ICE) 4.6.2 [37].

2.3.1 Field test in Beijing for flow control

The basic idea of the field test was to examine the flow control effect of using the radiator valve in combination with automatic balancing valves. With these two devices, the hydraulic balance is established and the flow distributed to each radiator can be controlled around the design value.

2. 3.1.1 Configuration of the field test

This field test (Case-Beijing-B) was carried out in a new 18-storey high-rise residential building in Beijing, which is structurally similar to Case-Beijing-A. The building's appearance is shown in

Figure 7 (left). The heating installation configuration for each apartment is illustrated in

Figure 7 (right). Details of the devices used are listed in Table 1. It should be mentioned that the radiator valves and the automatic balancing valves either need to be pre-set, or set during commissioning when the heating season starts, so that the radiators can achieve the required design flow under peak load. The set values of these two devices would be kept throughout the heating season or slightly adjusted if necessary. This field test focuses on the flow control effect of using these two devices, so the thermostats were removed for the experiment. In addition, automatic weather compensation control was applied at substation level for Case-Beijing-B to control the supply temperature, and variable speed pumps were available on the secondary-side of this DH system.

Table 1. Details of the relevant devices installed in tested apartment

Device name		Type	Dimension
Radiator valve		RA-N[21]	DN15 (mm)
Auto balancing valves	DP controller	ASV-PV[23]	DN20 (mm)
	Partner valve	ASV-M[23]	DN20 (mm)
Ultrasonic energy meter		SONOMETER 1100[24]	DN20 (mm)

The radiator valves were mounted on the radiator pipework. All the other devices mentioned above were installed in the staircase/hall (see

Figure 7 (right)), which was the location of the heat entry point for the apartment heating systems.

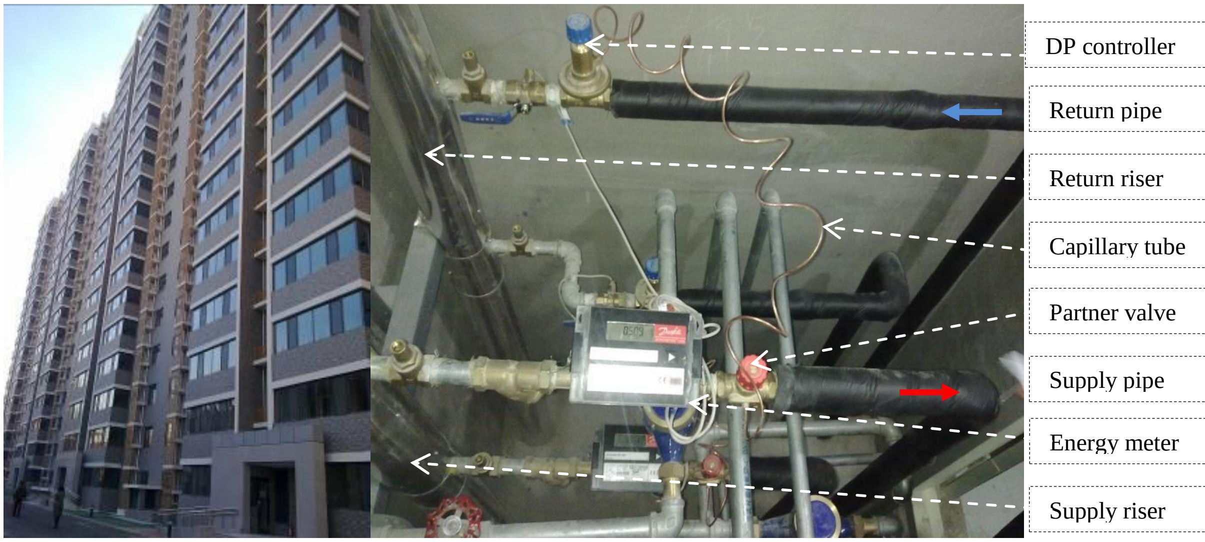

Figure 7. Real test case for the flow control approach

2. 3.1.2 Implementation of the field test

The field test consisted of two parts: Test I considered three apartments as test objects and focused on the pressure control function of the DP controller. Test II considered one apartment as the test object and focused on the flow limitation function of the radiator valve pre-setting function. Throughout the test, the other apartments' heating systems in this building were operating normally.

In Test I, three apartments with identical heating areas were chosen as the test objects. They were located on the right-hand side of the 2nd floor (201), the left-hand side of the 2nd floor (202), and the right-hand side of the 17th floor (1701). During the test, all the radiator valves were pre-set to N, i.e. the radiator valves were fully open.

The apartment loop flows were measured for apartments 201, 202, and 1701 when the DP controllers were in turn set at 5, 10, 15, 20, and 25 kPa. The ultrasonic energy meter of each apartment was used to measure the flow and investigate: 1) the hydraulic situation along the vertical pipe; 2) the flow changes in one apartment loop resulting from changing the set points of the DP controller at random or completely shutting off the loop flow of the other two apartments.

In Test II, one of the apartments was chosen as the test object. The aim of Test II was to investigate how the pre-setting function of the radiator valve controls the flow rate of the heating system. This apartment had five rooms with their own radiators and was located on the 2nd floor. Basic data about the apartment are given in Table 2. Each radiator was equipped with a radiator valve with pre-setting function. Test II was performed with the DP controller set at 10 kPa in accordance with EN 215 [25]. The design parameters of this heating system (supply/return/indoor temperature) were 75/60/18 °C. The design flow for each radiator could therefore be calculated and is given in Table 2. Based on the pressure drop of the heating loop and the design flow of the radiator, the pre-set scales of the radiator valve were determined and are listed in Table 2. The schematic configuration of the apartment-heating loop is illustrated in Figure 5. A Testo 925 [40] was used for measuring the indoor temperature.

Table 2. Basic information about the apartment tested

Room name	Floor area (m^2)	Heat load (W)	Desired operating temperature difference (°C)	Desired flow (l/h)	Pre-set values of the radiator valve
Living Room	18	810	15	46.4	3
Bedroom A	14.5	654	15	37.5	2.5
Bedroom B	8.7	391	15	22.5	1.5
Bathroom	3.4	168	15	9.6	1
Kitchen	4	180	15	10.3	1
Total	48.6	2203		126	

2.3.2 IDA-ICE simulation for indoor temperature control

For the indoor temperature control investigation, a simulation model of an eight-storey residential building was developed using IDA-ICE 4.2.6 [37]. To develop this building model, the building layout and building materials of one of the buildings in Case-Harbin were used. The building envelope properties and the thermal characteristics were as specified in China's energy conservation design standard JGJ26-95 [41]. One of the apartments was modelled as a multi-zone model. Each room in the apartment was a separate zone. The room height was 2.7 m. This multi-zone model contained five heated zone areas: Bedroom N (north), Bathroom, Bedroom S (south), Kitchen, and Living Room, as well as three non-heated balconies and a non-heated staircase/hall (see *Figure 8*). The outdoor heating design temperature was -26 °C for Harbin and the indoor design room temperature was 18 °C. Based on the information, we run the multi-zone model equipped with ideal radiators, and obtained the peak heat load of each zone.

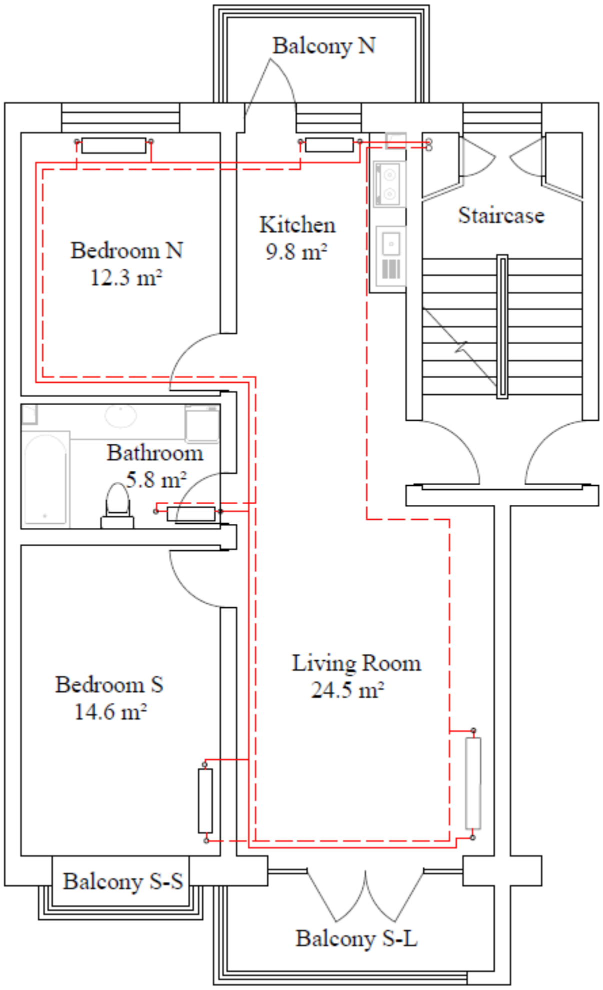

Figure 8. Multi-zone model

We dimensioned the radiators in accordance with Chinese standard [10]. In each zone, an M132-type radiator [42] was modelled as the room heating unit as in Case-Harbin. The design parameters of the SH system were the same as those for Case-Harbin: 80/60/18 °C (supply/return/indoor air temperatures). Correction factors were derived to correct for the actual output of each radiator. Accordingly, the maximum power of each radiator was determined, and the design flow limitation through the radiators and the design heat load for the SH system were defined.

Linear fit-to-metered supply temperatures were chosen in relationship to the outdoor temperatures shown in Figure 4. Here the secondary supply temperature is assumed to have been optimized by applying the weather compensation control at the substation and variable speed pumps in the secondary network of this system. To reflect the real conditions, an internal heat gain of 5.0 W/m^2 was considered [41]. Real weather data in Harbin city in 2014 was used to estimate the energy consumption for heating using EnergyPlus [43]. Two scenarios were considered: 1) without TRVs fitted to the radiators, which is the most common situation in Chinese SH systems; and 2) with TRVs fitted to the radiators to adjust the indoor temperature by setting the thermostat of the

TRVs. The room temperature of each zone, the energy consumption including heat consumption, and the electricity consumption of the pumps as well as the volume flow of the heating system were all compared based on the simulation results.

3. Results and Discussion

3.1 Field test in Beijing

3.1.1 Test I: Differential pressure control of the apartment heating loop

The test objects for Test I were three apartments 201, 202, and 1701.

The first aim of the investigation was to test whether the three test heating loops had the same distributed flow when the set points of the DP controllers were the same. The measurement results are shown in Figure 9. When the DP controllers of the three apartments loop were given the same set point (separately set at 5, 10, 15, 20, and 25 kPa), the three loops had a similar volume flow as expected. The deviation of the individual loop flow from the average flow of these three loops at the same set points was within ±15% (see Figure 9). This deviation can be considered as acceptable, because the set points of the DP controllers were adjusted by manually turning the spindle and there were no pressure gauges in the supply and return pipes to measure the pressure drop of the loops directly. Moreover, mechanical hysteresis influences the variations and causes a difference in the measured flow rates. The 2nd floor and 17th floor have identical floor heating areas, so theoretically the distributed flow could be the same. It can therefore be concluded that the hydraulic imbalance along the vertical riser was reduced after the installation of the DP controllers.

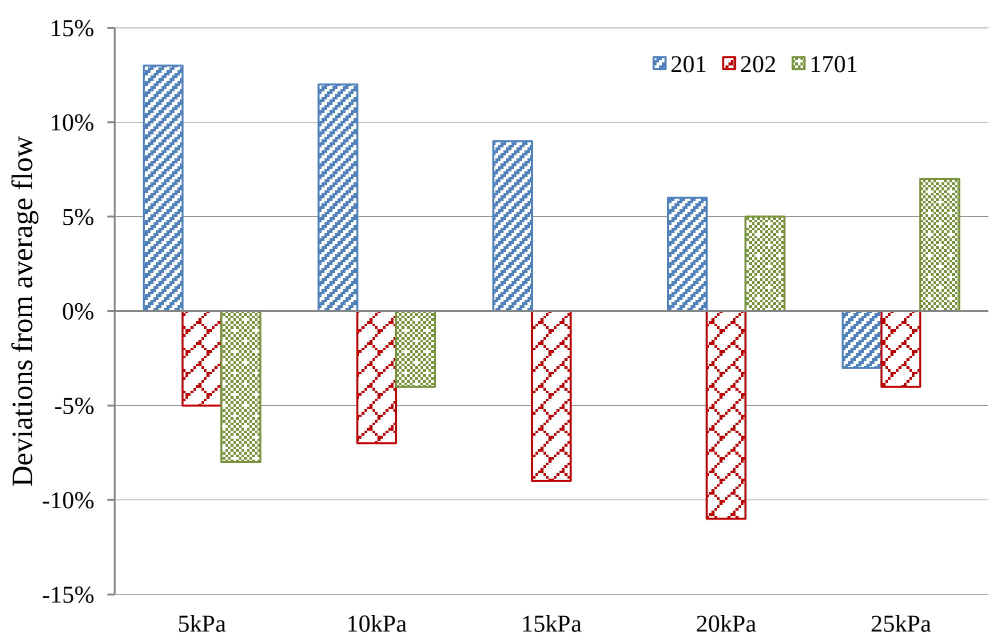

Figure 9. Deviations from the average flows of 201, 202, and 1701 at various set values of the DP controllers

The second aim of Test I was to test whether one of the heating loops was pressure-independent when the differential pressure of the other two heating loops changed. The results show that when the differential pressure of the other two tested heating loops was changed by adjusting the set points of the DP controllers or by completely shutting off the loops, the other apartments' heating systems kept operating normally and the flow of the third tested loop was not influenced or changed. This means that the automatic balancing valves were able to separate each heating loop as an independent pressure zone, and maintain the constant differential pressure in the controlled loop. It also implies that the DP controller controls the differential pressure across the controlled loop, which will ensure an optimal differential pressure across the downstream control valves. In this way, the flow within the controlled loop would not be affected by any system load changes, and noise would be avoided.

3.1.2 Test II: The pre-setting function of the radiator valves

For Test II, the test object was one apartment.

The apartment loop's mass flow, the supply and return temperatures, and the indoor temperature were measured with the set point of the DP controller at 10 kPa. The measurements were first carried out without radiator valves pre-set, and after that with them all pre-set. The mass flow measurement results (see Table 3) showed that after the radiator valves were pre-set, the total flow supplied to the apartment was reduced to 1/3, from 557l/h with no pre-setting to 181 l/h with pre-set. This implies that the flow rate through each radiator was limited dramatically by the pre-setting function. The flow rate in the case of pre-setting was close to the design flow rate of 126 l/h. This indicates that flow control by pre-setting the radiator valves on the terminal heat units is effective. The temperature measurement results showed that the temperature difference of the controlled loop increased by nearly 100% with the radiator valves pre-set, changing from 9 ºC to 17.3 ºC. Test II focused on the hydraulic control effect of pre-setting the radiator valves. The results clearly show that the large flow and small temperature difference problem which is typical in Chinese DH systems has been significantly relieved. This is the most important result that the test aimed to get. It also reflects the great energy-saving potential if the excess flow can be controlled.

In addition, at the start of the test, when there was no pre-setting of the radiator valves, the room temperature was 22.6 ºC (see Table 3), with heating power of 5.8 kW. The design capacity is 2.2 kW for -9 ºC outdoor air temperature. Due to lack of individual controls, the tenants regulate the room temperature by opening windows, which explains why the room temperature was no higher. After the pre-setting of the radiator valves, the delivered capacity was 3.6 kW and the room temperature went down to 22 ºC within two hours. A further decrease might be expected, but the 3.6 kW would be more than enough to sustain 18 ºC room temperature, seen in relation to the design capacity.

Table 3. Temperature measurement comparison between with and without pre-setting in Test II

Parameter of tested apartment loop	No pre-setting	Pre-setting
Total flow of apartment loop (l/h)	557	181
Supply temperature (°C)	62.6	62
Return temperature (°C)	53.6	44.7
Delta T (°C)	9	17.3

Average indoor temperature (°C)	22.6	22
Outdoor temperature (°C)	-4	-4

The field test showed that pre-setting radiator valves combined with the automatic balancing valves could control the loop flow close to the design level. Within the apartment loop, pre-setting the radiator valves limited the maximum flow of each radiator and created the right balance among the radiators. Flow limitation for each terminal heat unit prevented insufficient flow at distal units and excess flow at proximal ones. It reduces the total supplied flow and consequently the pump electricity consumption.

The differential pressure limitation of the automatic balancing valves provided the appropriate pressure drop over the radiator valves. The hydraulic imbalance along the vertical riser was reduced, and it guaranteed to set the thermostat properly to adjust the indoor temperature. At the same time, the noise from the radiator valves was avoided. Further adjustments of the room temperature towards the desired temperature could be achieved by adding a thermostat to the radiator valve, which would adjust the valve depending on the deviation from the set-point temperature of the TRVs.

In this field test, a dynamic hydraulic balance was created in the heating system by using pre-set radiator valves combined with automatic balancing valves. Every loop received the required flow and excess flow and insufficient flow were avoided. Every room received the required heat. Flow limitation improved the efficiency of the pump, and increased the temperature drop across the radiator. This field test indicates that the excess heat loss can be reduced through establishing dynamic hydraulic balancing in the building heating system.

3.2 IDA-ICE simulation

3.2.1 Model validation

The radiator heating system in the multi-zone model was designed in accordance with the Chinese design standard. The “linear fit-to-metered supply temperature” from CASE-Harbin (see Figure 4) defined the supply temperatures of the simulated heating system during the heating period. As shown in Figure 10 , the simulated return temperatures were compared with the linear fit-to-metered return temperatures from Case-Harbin. The results show that the deviation between the simulation results and the linear fit-to-return temperatures from Case-Harbin was on average about 2 ºC. It should be mentioned that the measurements from Case-Harbin were acquired at the area substation and were the average return temperatures from all the connected buildings. The deviation between the model outputs and the measured return temperatures were therefore considered to be acceptable and the model was considered valid.

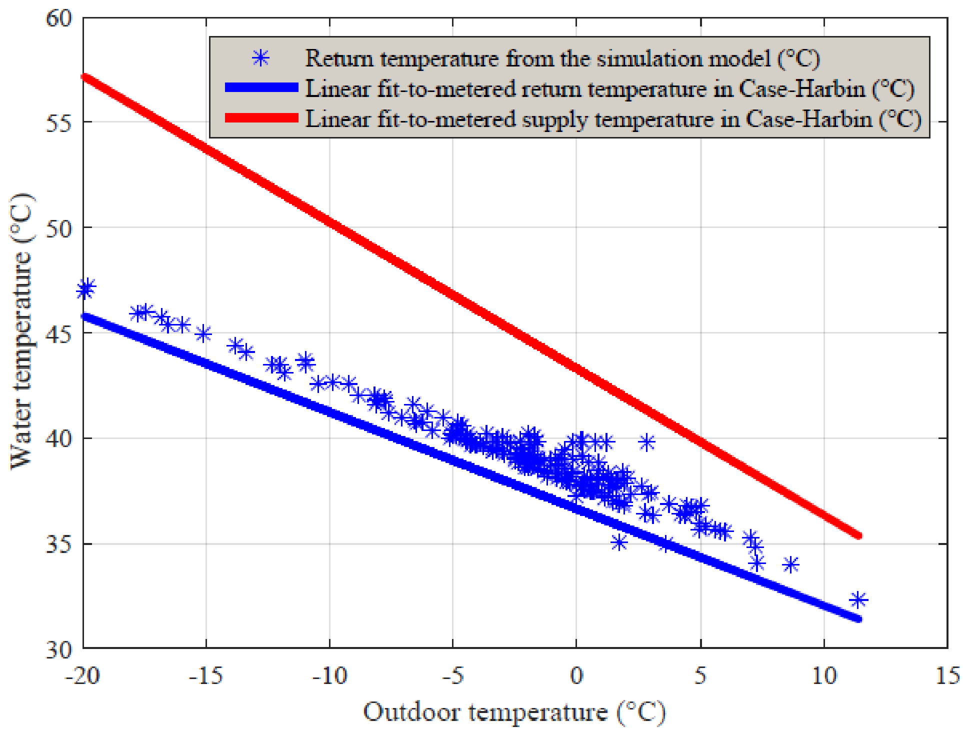

Figure 10. Supply and return temperatures for the model of the SH system

3.2.2 IDA-ICE simulation results

A simulation was carried out for the heating period in Harbin for two scenarios: radiators without TRVs and with TRVs. Several factors were considered in the simulation: room temperatures, heat consumption, pump electricity consumption, and the flow rate in the heating system.

Firstly, in terms of the room temperatures, the general results showed that without TRVs the room temperatures in all the zones were much higher than 18 ºC except for a few hours at the beginning of the heating period. The average room temperatures in all five zones over the entire heating period were around 22 ºC. With TRV control, the room temperatures in all the zones were constant at around 18 ºC. There are some minor deviations between the set temperature and the simulated room temperature, due to the 0.5 ºC proportional band (P-band). Because TRVs are proportional temperature controllers, they respond to any deviation from the set temperature by increasing or decreasing the flow into the radiators until the required room temperature is achieved. Figure 11 shows the simulation results for two typical rooms in the multi-zone model: the northern room 'Bedroom N' and the largest room the 'Living Room', which reflects these small variations particularly clearly. The indoor air temperature can also be seen to have lagged a few days behind outdoor temperatures changes because of the thermal inertia of the building envelope materials.

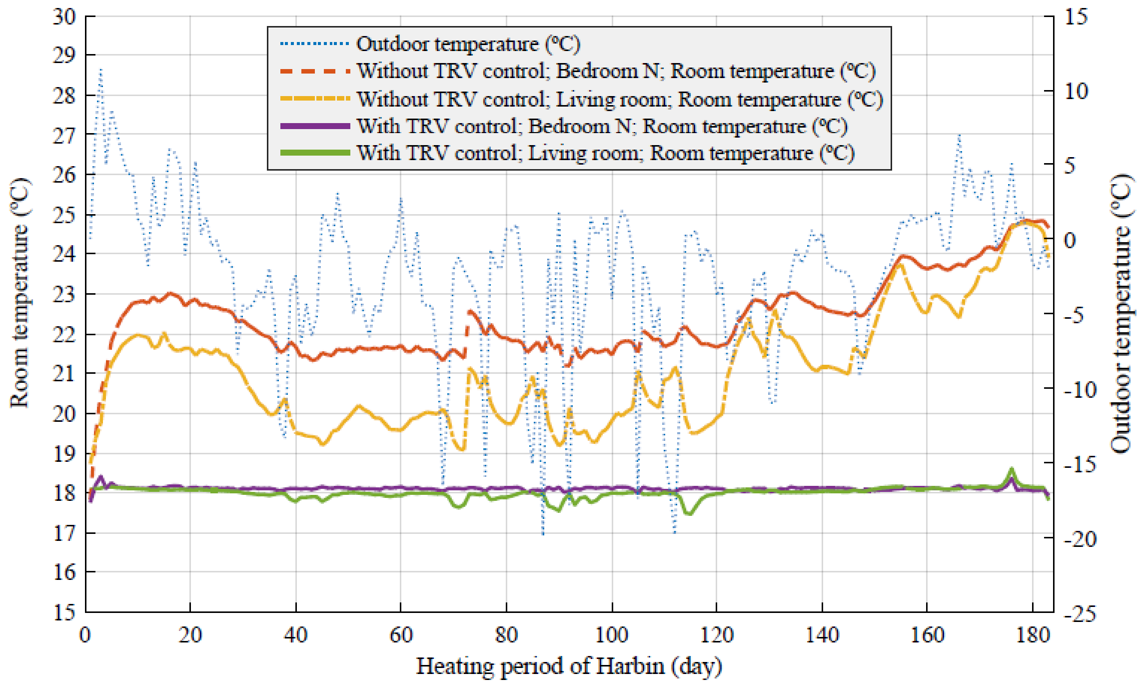

Figure 11. Zone room temperature of Bedroom N and the Living Room during the heating period

As shown in the simulation results, the application of TRVs provides the practical possibility for the room occupants to adjust the room temperature. When the rooms are overheated, the indoor temperature can be adjusted by setting the thermostat rather than opening the windows. Thermal comfort can imply multiple factors like indoor temperature, humidity, and draught [44]. But in the heating supply context, thermal comfort mainly refers to the indoor room temperature. In an unbalanced system, the thermal discomfort means excess heating for users close to the substation and insufficient heating for users far away from the substation. Through the implementation of the technical approach presented here, the indoor temperatures for rooms in different locations are balanced and close to the design room temperatures. We therefore conclude that the indoor thermal comfort is improved.

Correct use of TVRs has the potential to achieve great energy-saving effects. In some cases, heat consumers might not know how to use the TRVs correctly and might simply use the maximum set point, which will compromise the energy savings potential. The set points can be protected and locked by inserting the pins on the dial, and an energy-saving type of TRV can be used with a maximum set point of 20 ºC [45].

Secondly, the monthly heat consumption and pump electricity consumption were compared for the two scenarios, and the results are shown in Figure 12. Since the heating season is fixed in Harbin city and does not include May to September, no data were collected for those months. In terms of annual energy consumption, which was obtained by accumulating the monthly energy consumption over the heating season, the results imply that applying TRVs can reduce annual heat consumption by 17% and annual pump electricity consumption by 42.8% for this particular apartment. Here it should be noted that the pump energy consumption is very small compared to the heating energy consumption, only 0.1% of the heat energy delivered.

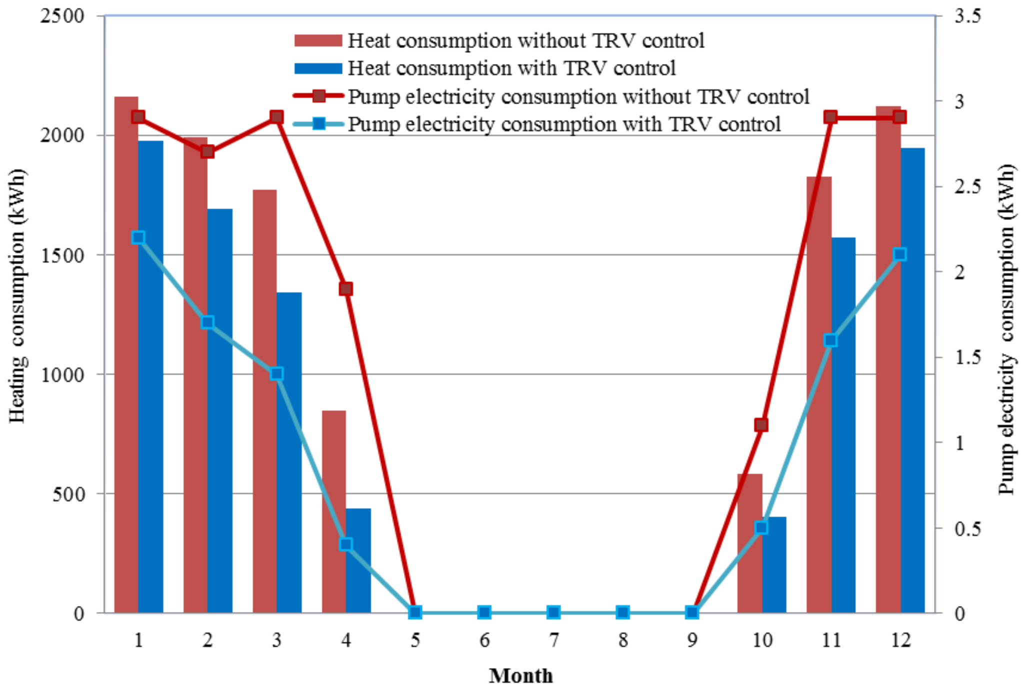

Figure 12. Heat consumption comparison between the scenarios with and without TRV control

Coal is the dominant DH fuel, and the dominant fuel for Chinese power plants. Burning coal is one of the main causes of air pollution in China [46]. Hydraulic balance can achieve 17% heat savings and 42.8% pump electricity savings. This will result in positive environmental impacts. In Case-Harbin, the total heating area in 2013-2014 heating season was 442,340 m^2. The measured seasonal heat consumption per m^2 was 0.7GJ/m^2, and the seasonal pump electricity consumption was 2.1 kWh/m^2. This reflects the currently unbalanced system situation. With hydraulic balance, the simulation results show that the seasonal heat consumption could be reduced by 0.12 GJ/m^2, and the seasonal pump electricity consumption could be reduced by 0.9kWh/m^2. The results imply that the total emission reduction for Case-Harbin could have been 4837 ton of CO_2, 44.7 tons of SO_2, and 13 tons of NO_x in the 2013-2014 heating season if hydraulic balance had been achieved. Therefore, the seasonal environmental impacts would reflect the reduction of 11kg CO_2, 0.1g SO_2, and 0.03g NO_x per heating square metre.

Moreover, with regard to the system's operation, it is important to note that applying TRVs changes the SH system from constant flow to variable flow (see Figure 13).

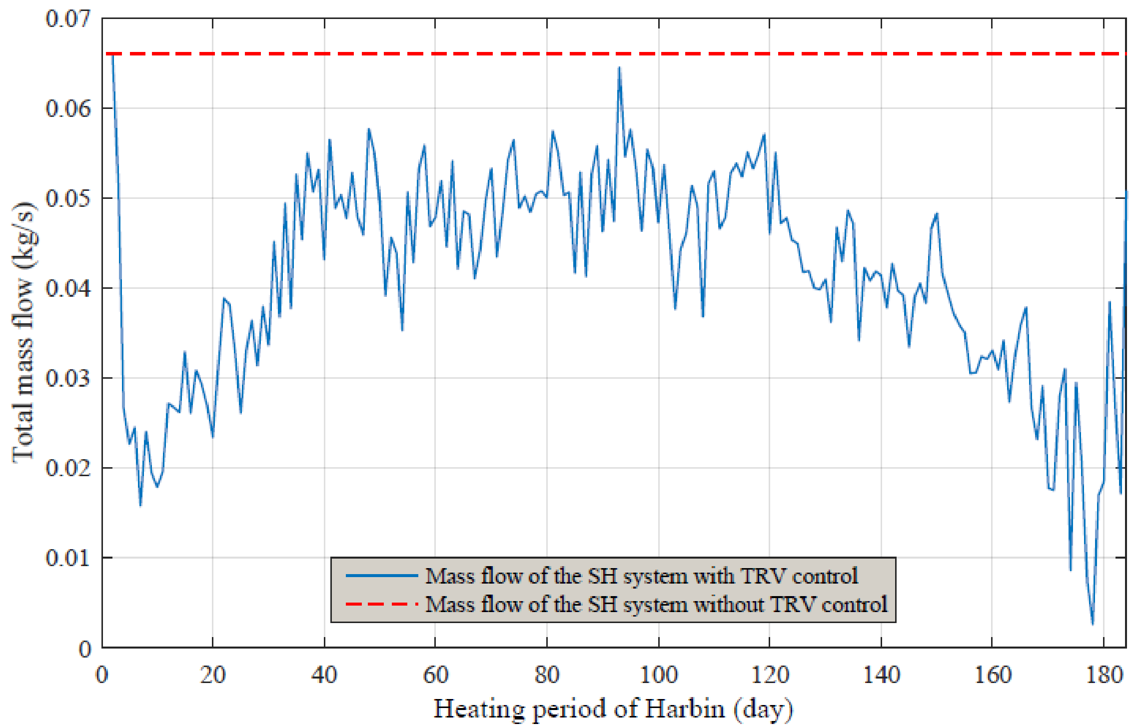

Figure 13. Total mass flow comparison between scenarios with and without TRV control

According to the results from the field test and the IDA-ICE simulation, the excess heat loss can be reduced by achieving hydraulic balance and optimizing indoor air temperature control at the building level.

In this study, the research object was the building heating system. Energy reduction at the building level will inevitably impact the whole DH system, reducing the amount of heat that area-substations have to deliver to a group of buildings and that the heat source plants have to deliver to the area-substations.

Dynamic hydraulic balancing ensures the apartment heating loops distribute the requested flow, with neither excess flow nor inadequate flow. Moreover, it means that the apartment heating loops are not influenced by each other if adjustments are made. Temperature control stabilizes the room temperature at comfort levels and avoids the room overheating. The integrated technical approach therefore reduces excess heat supply and excess heat loss. This means lower fuel consumption and less polluting emissions due to the fossil fuels heavily used in China. The economic benefits and environmental effects achieved will be considerable.

In the future, along with the energy consumption reduction in space heating systems, it is expected that Chinese DH systems will transition from the current centrally planned heat supply to demand-driven heat generation, which will also give increased comfort for users. In addition to this improvement in quality of life, DHW could also be integrated into DH systems to supply hot water in the future. This would be possible because the reduction in excess heat supply will result in large energy savings.

The high building density in Chinese' cities and the continuously expanding heating areas with rapid urbanization mean that there will be significant heat demands that need to be fulfilled. This emphasizes the significance of the kind of reductions in energy consumption in Chinese DH systems discussed in this paper.

4. Conclusions

To conclude, the proposed approach of combining the use of TRVs with an integrated pre-setting function and automatic balancing valves has been shown to be both feasible and effective in practice.

Firstly, a field test showed that pre-setting radiator valves combined with automatic balancing valves can establish dynamic hydraulic balance in a building heating system. Each controlled loop becomes an independent zone. The pre-setting of the radiator valve is an important function to equalize the flow distribution among the terminal heating units. Moreover, automatic balancing valves enable the radiator valves to work at optimum differential pressure level. As a result, the problems of excess flow and insufficient flow are avoided in the heating system. At the same time, the return temperature was decreased, and the temperature drop across the radiator was increased.

Secondly, IDA-ICE simulation results indicate that TRVs stabilize the room temperature. Wide use of TRVs in Chinese buildings can reduce heat consumption by 17% and pump electricity consumption by 42.8%, compared to a scenario without TRV control. In addition, adjusting TRVs transform the system from constant flow to variable flow. Variable speed pumps can be applied with variable flow rate. As coal is the dominant fuel for DH plants and power plants in China, the savings on both heat consumption and pump electricity consumption imply the positive environmental impacts.

Traditional Chinese DH systems seldom have control at the consumer end. By moving the control close to the end users, it is possible to bring the heating supply into line with the heating demand. The integrated assessment method and field test show that a well-balanced DH system can improve consumer thermal comfort and at the same time save significant pumping power. A well-balanced DH system allows heat users to pay less if the heating is charged on the basis of the real consumption. The heat users are satisfied also due to the improved room temperature control. At the same time, it would also be cost-effective for DH utilities, who could increase their profits by avoiding excess heat loss.

The developed integrated approach will help the decision makers and stakeholders to plan new or renovated district heating projects to be more energy efficient and cost effective. It would make a considerable contribution to energy supply security and air pollution abatement for Chinese society by giving smart control to district heating systems.

Acknowledgements

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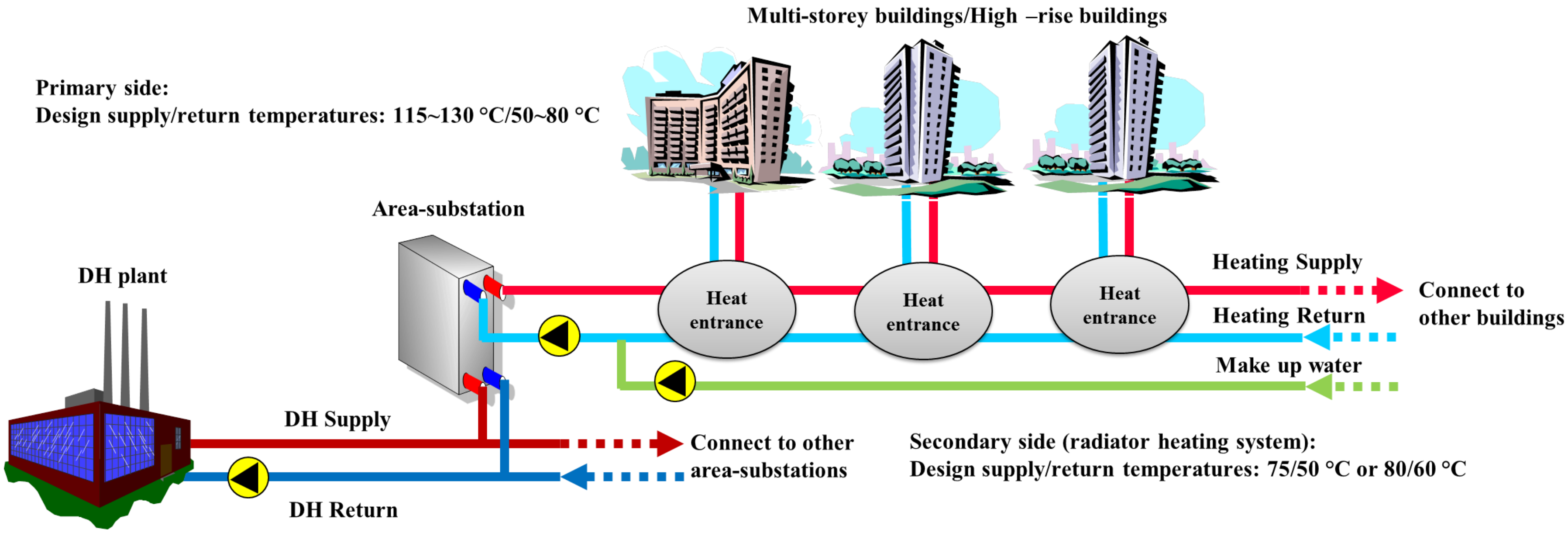
Figure

Figure 1. Typical district heating system used in China



Figure

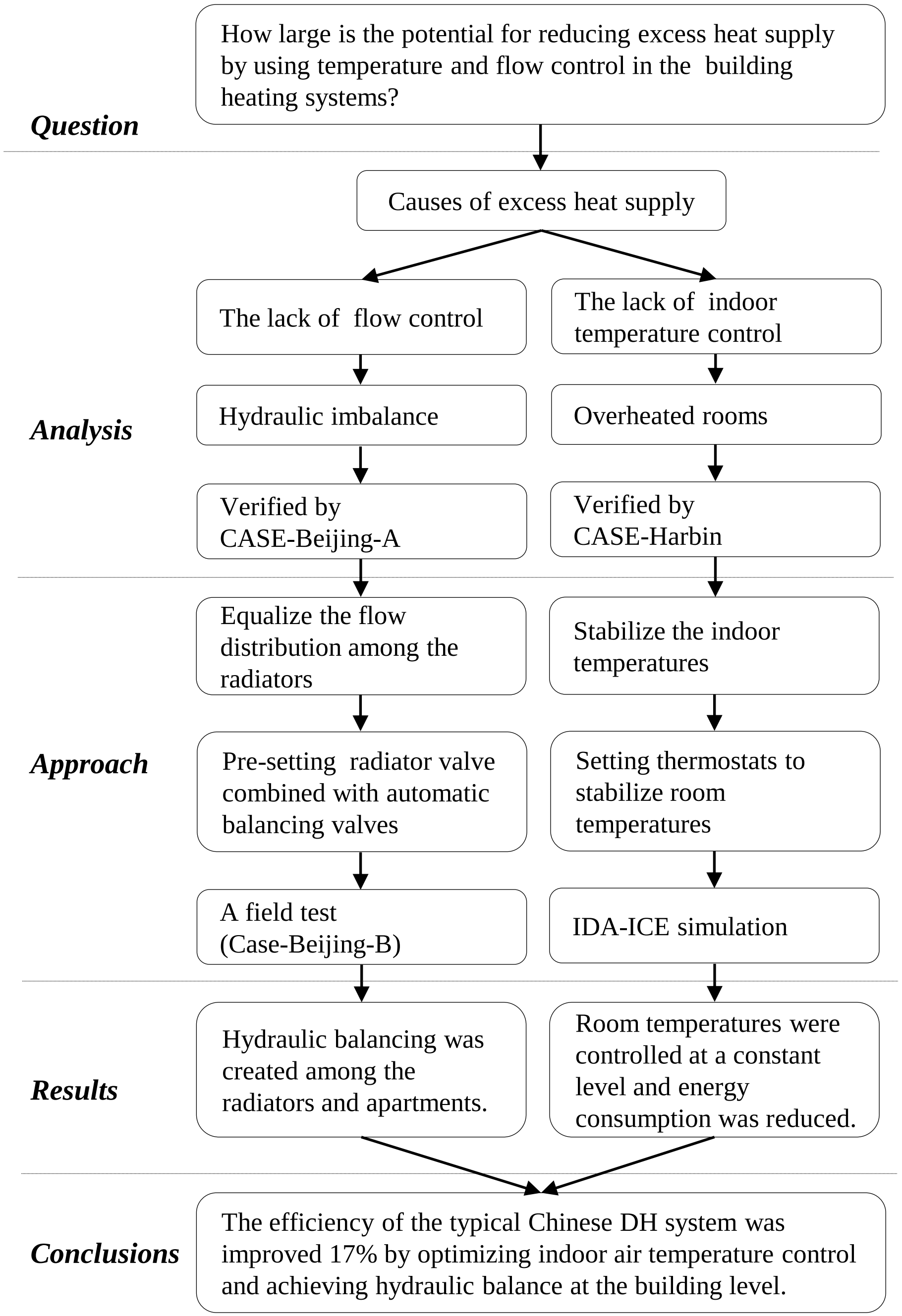


Figure 2. Flowchart of methods used in the study

Figure
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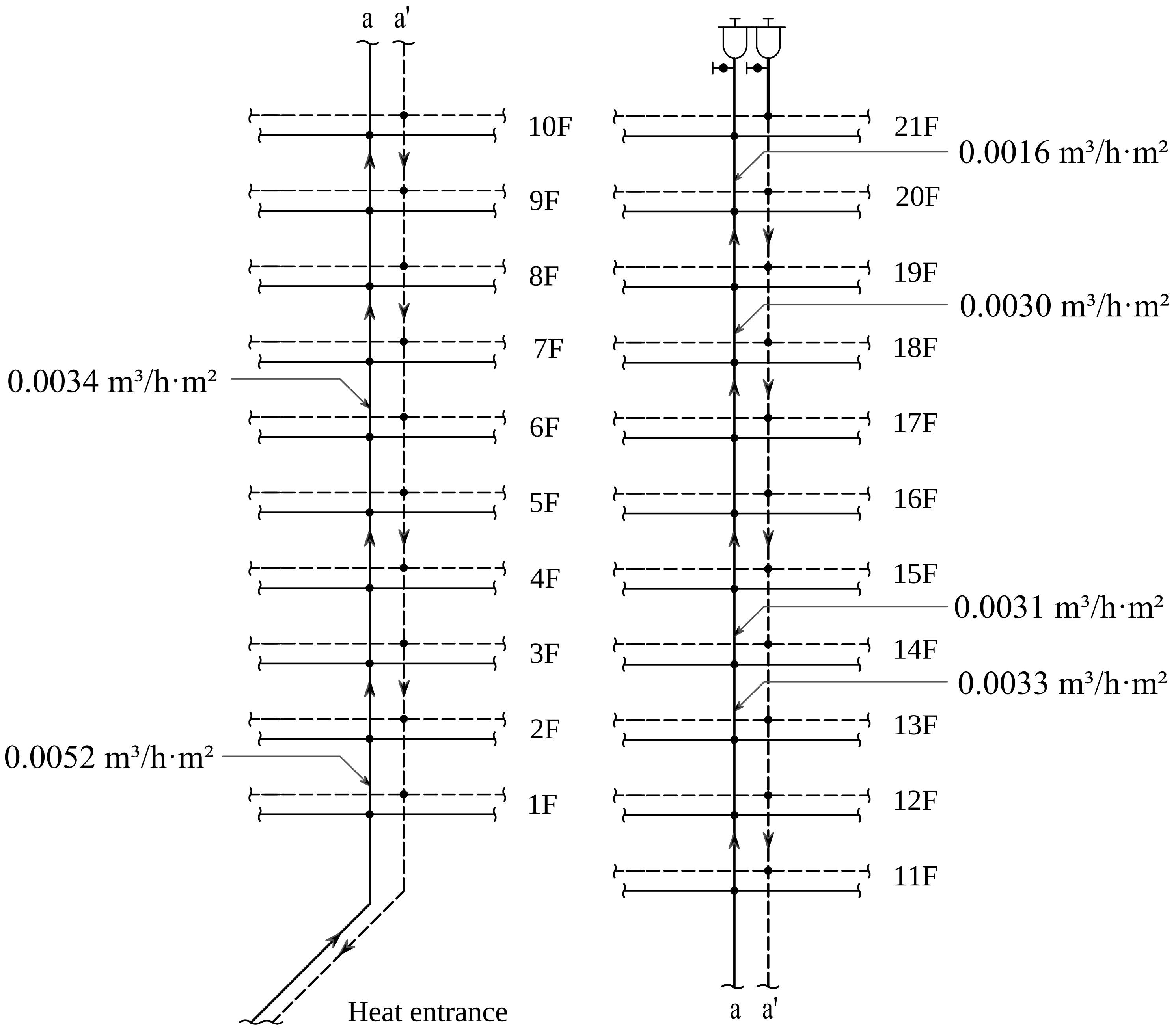
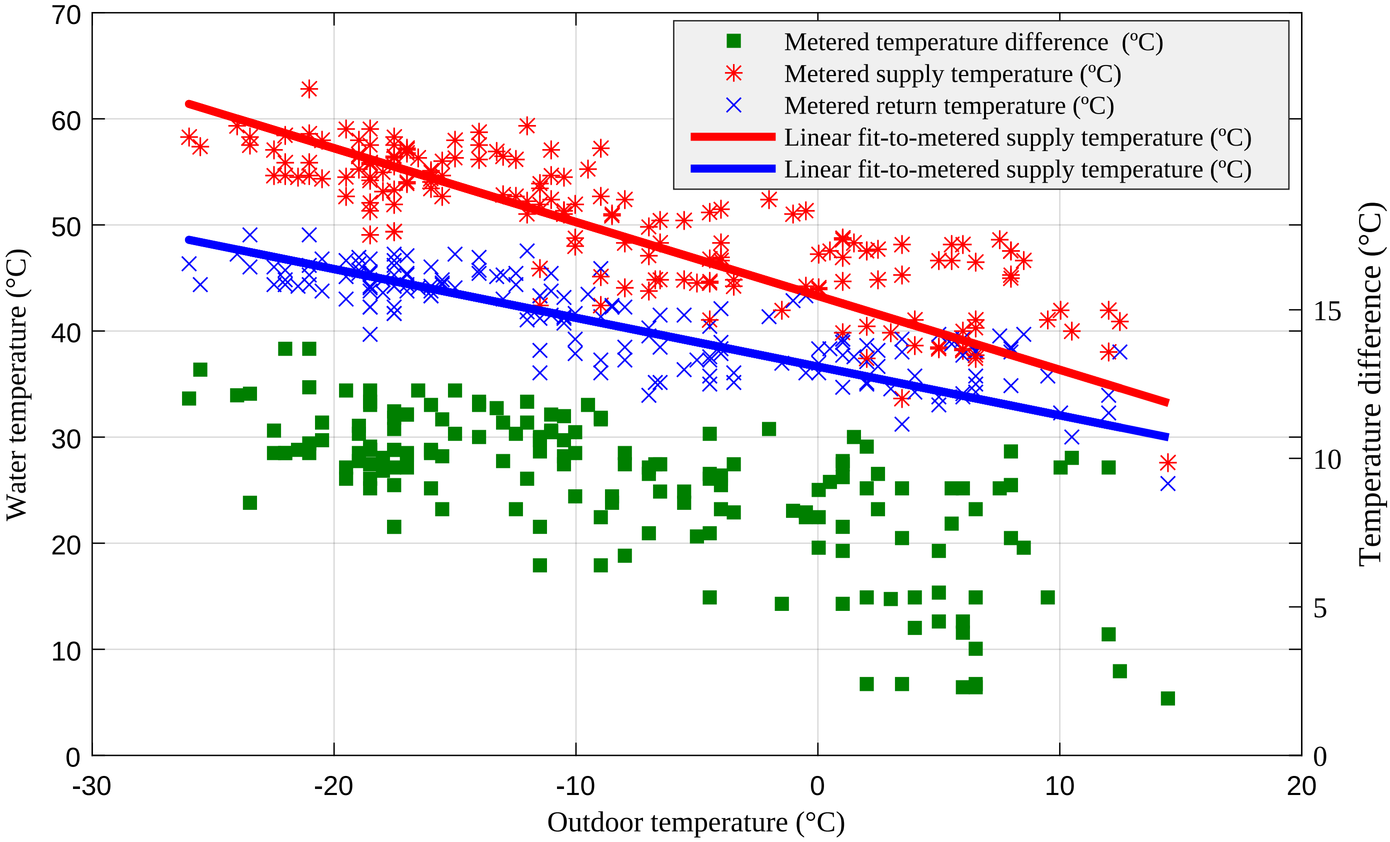
Figure



a
a'
10F
9F
8F
7F
6F
5F
4F
3F
2F
1F
0.0034 m³/h·m²
0.0052 m³/h·m²
Heat entrance
21F
20F
19F
18F
17F
16F
15F
14F
13F
12F
11F
0.0016 m³/h·m²
0.0030 m³/h·m²
0.0031 m³/h·m²
0.0033 m³/h·m²
a
a'

Figure



Metered temperature difference (ºC)
Metered supply temperature (ºC)
Metered return temperature (ºC)
Linear fit-to-metered supply temperature (ºC)
Linear fit-to-metered supply temperature (ºC)
Water temperature (°C)
Temperature difference (°C)
Outdoor temperature (°C)
70
60
50
40
30
20
10
0
15
10
5
0
-30
-20
-10
0
10
20

Figure

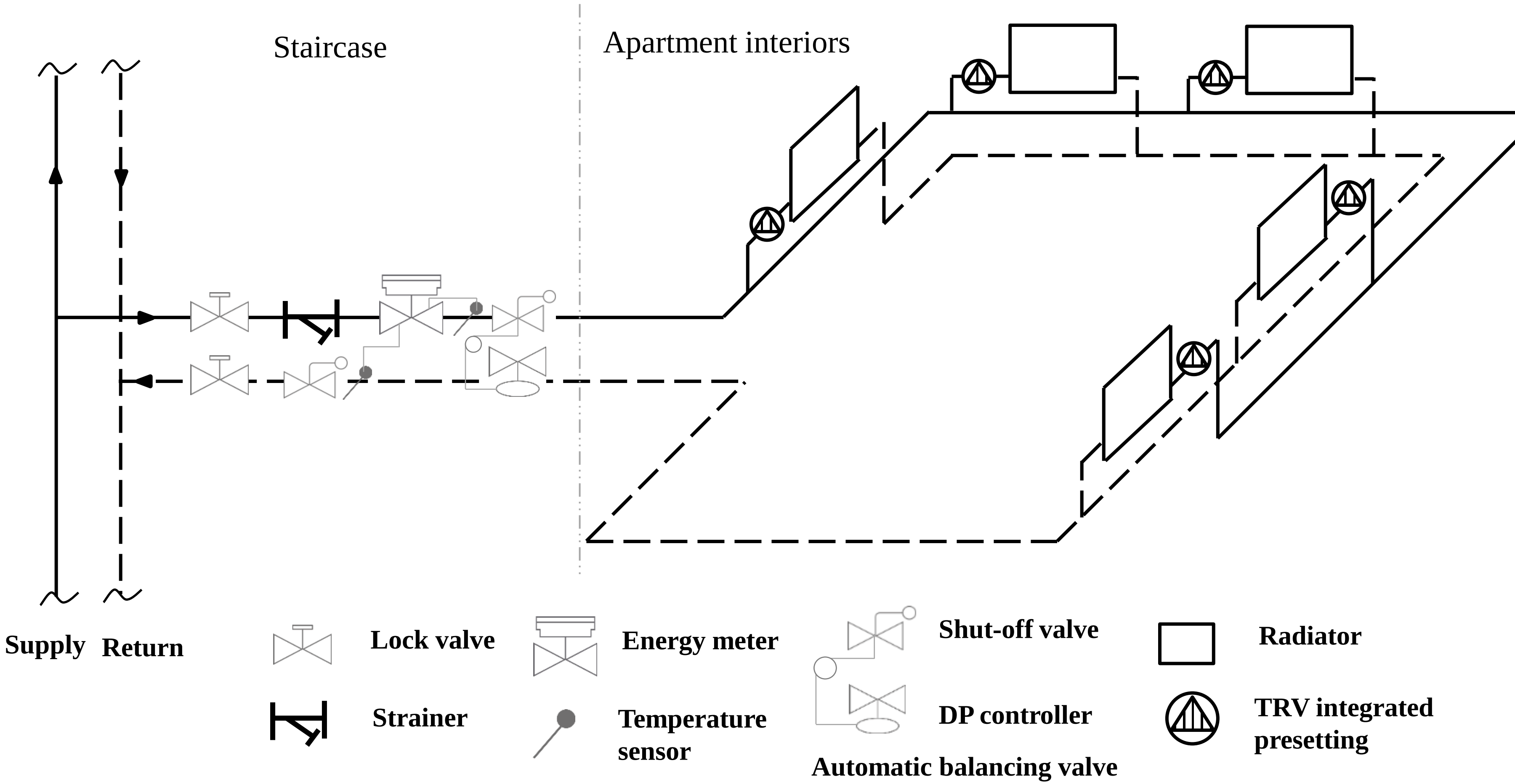
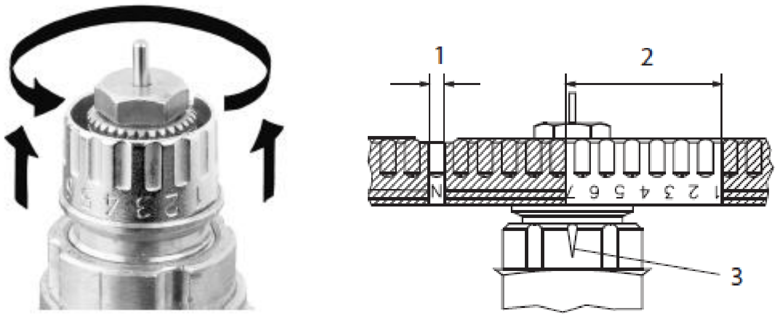


Figure 5. Schematic configuration of the apartment heating loop

Figure



1. Factory setting
2. Presetting range
3. Reference mark

Figure 6. Pre-setting scales of radiator valve [38]

Figure

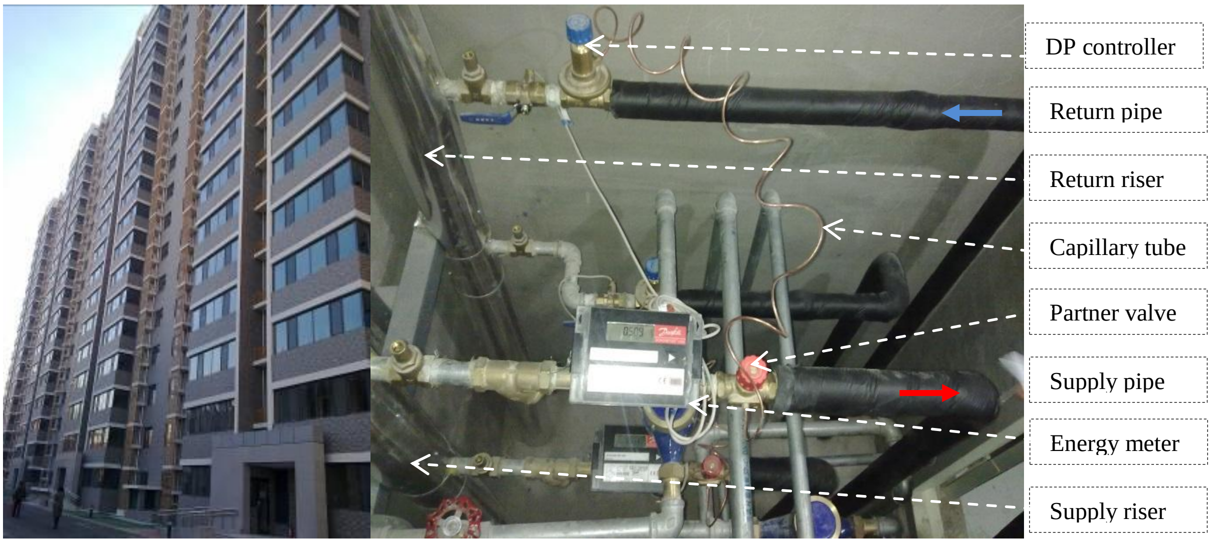
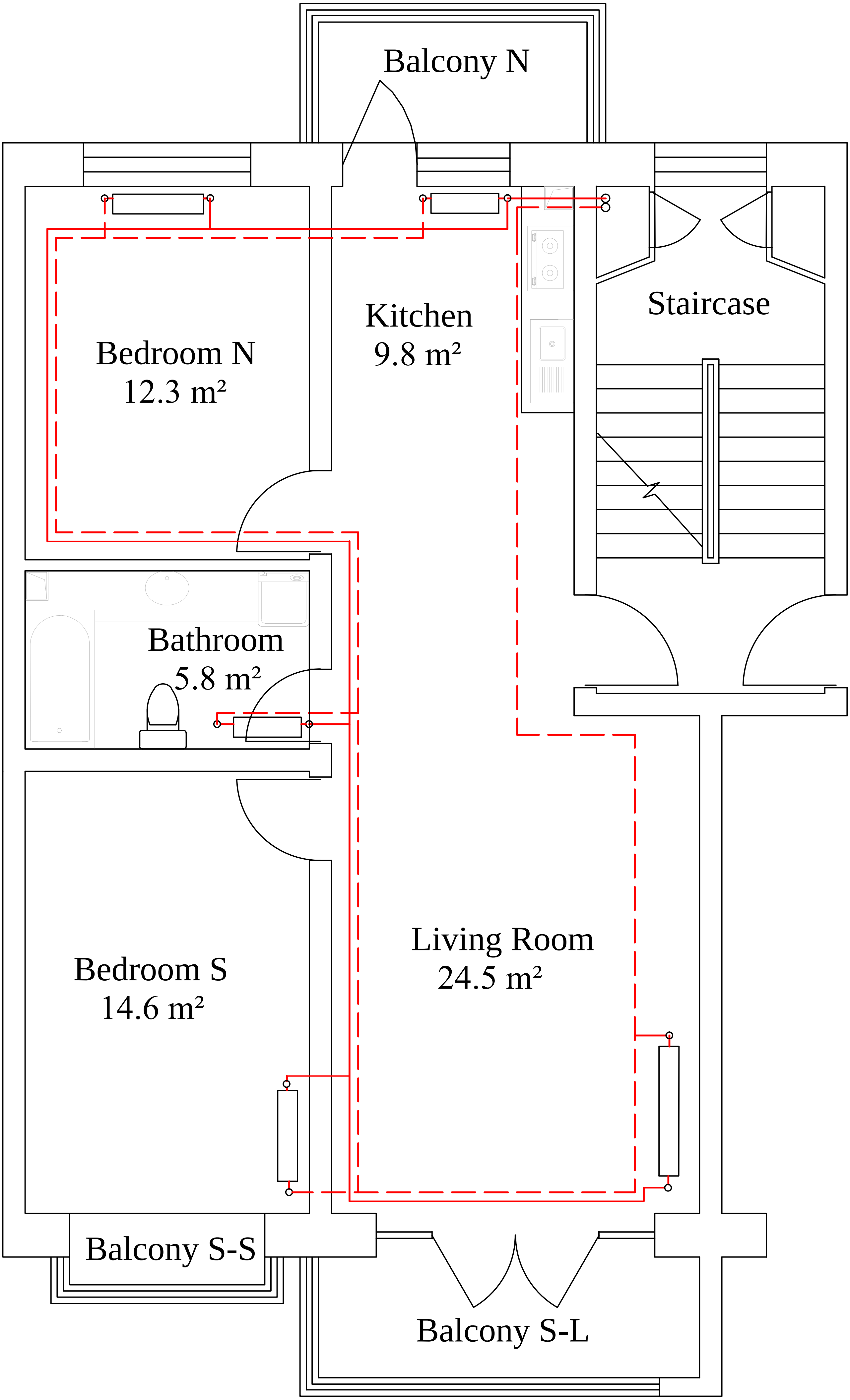


Figure 7. Real test case for the flow control approach

Figure



Balcony N
Bedroom N
12.3 m²
Kitchen
9.8 m²
Staircase
Bathroom
5.8 m²
Living Room
24.5 m²
Bedroom S
14.6 m²
Balcony S-S
Balcony S-L

Figure

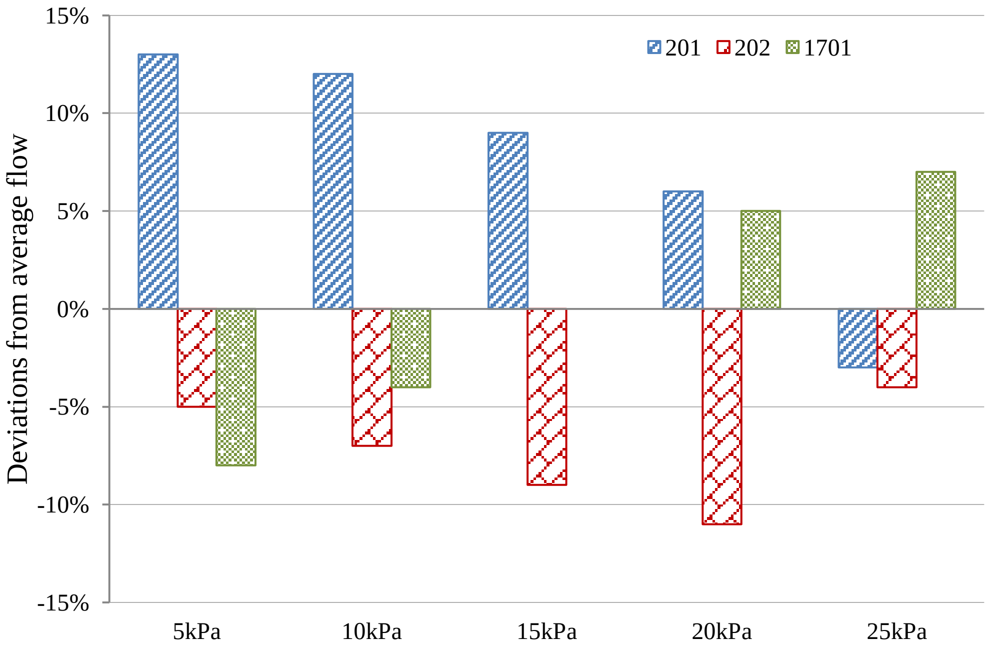
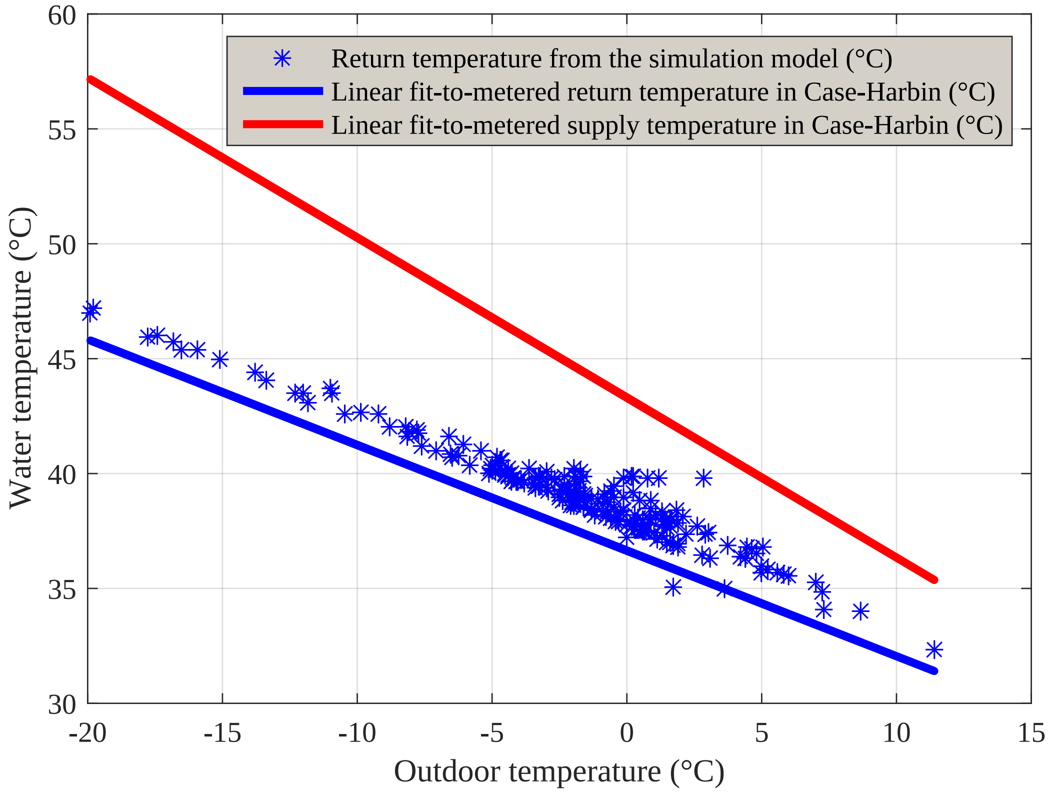


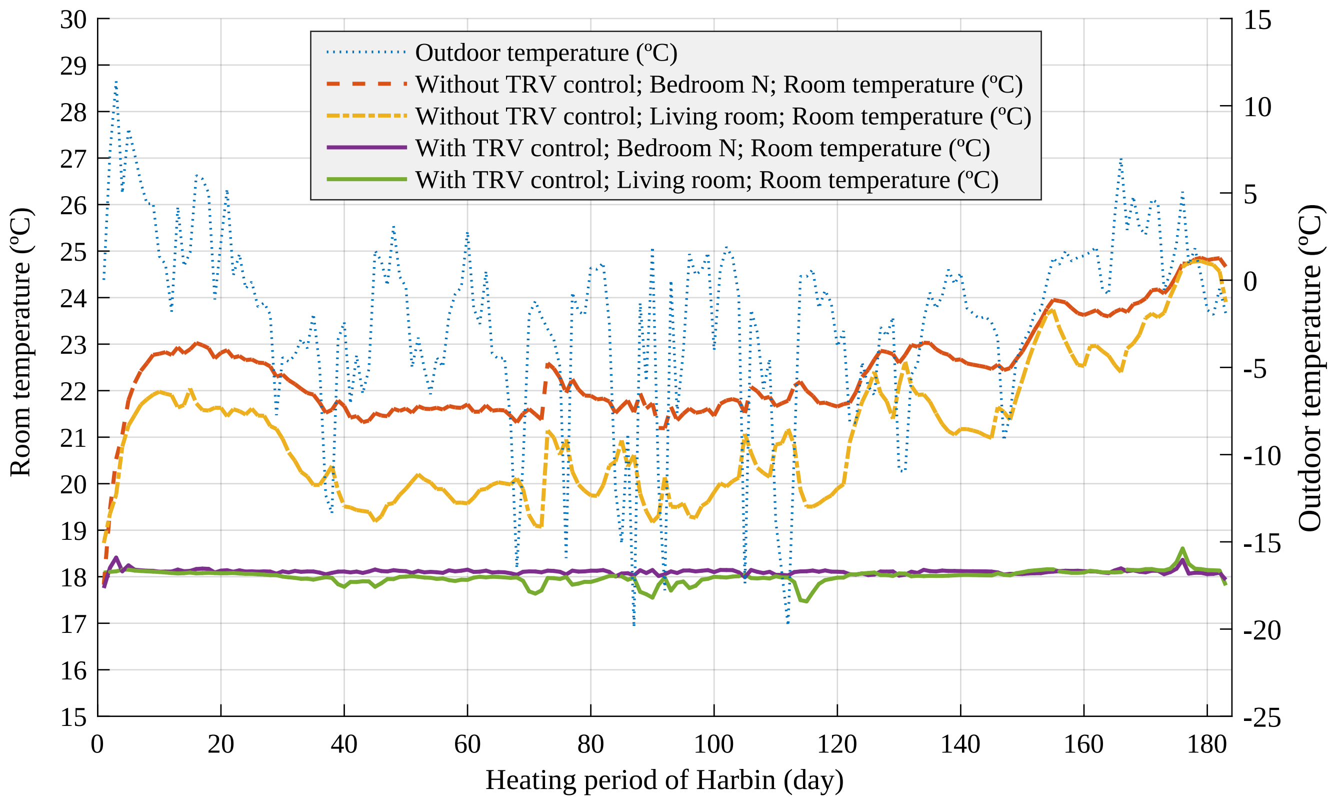
Figure 9. Deviations from the average flows of 201, 202, and 1701 at various set values of the DP controllers

Figure



Return temperature from the simulation model (°C)
Linear fit-to-metered return temperature in Case-Harbin (°C)
Linear fit-to-metered supply temperature in Case-Harbin (°C)
Water temperature (°C)
Outdoor temperature (°C)
60
55
50
45
40
35
30
-20
-15
-10
-5
0
5
10
15

Figure



Outdoor temperature (ºC)
Without TRV control; Bedroom N; Room temperature (ºC)
Without TRV control; Living room; Room temperature (ºC)
With TRV control; Bedroom N; Room temperature (ºC)
With TRV control; Living room; Room temperature (ºC)
Room temperature (ºC)
Outdoor temperature (ºC)
Heating period of Harbin (day)
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
15
10
5
0
-5
-10
-15
-20
-25
0
20
40
60
80
100
120
140
160
180

Figure

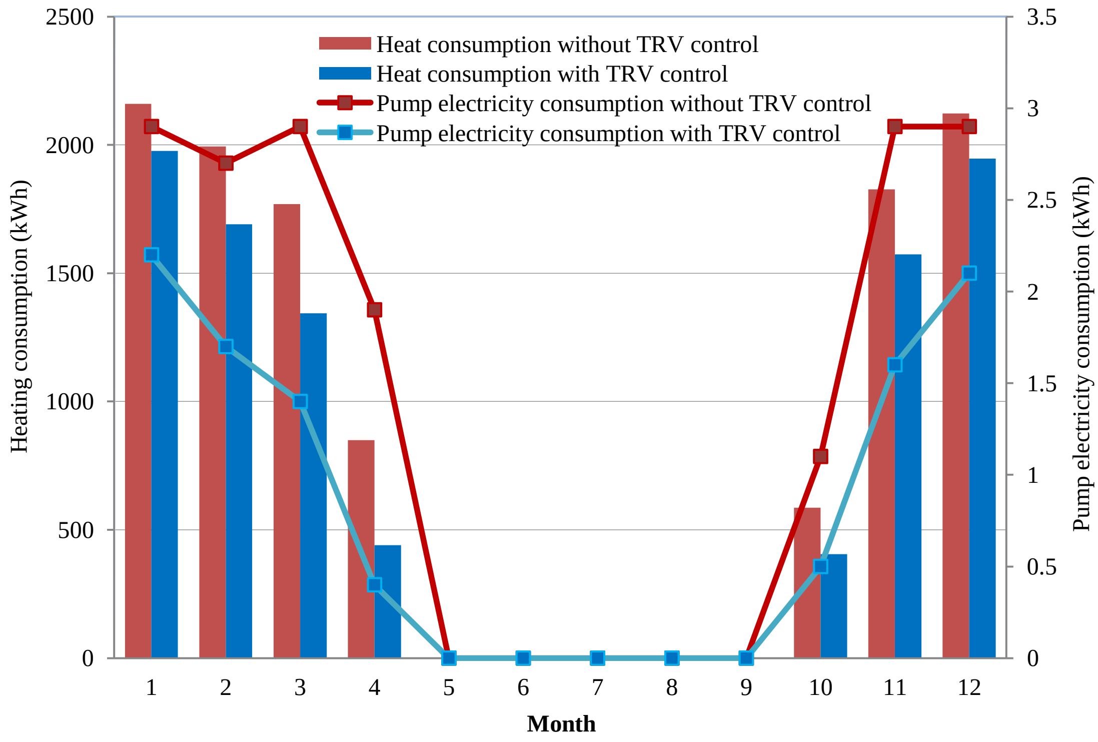
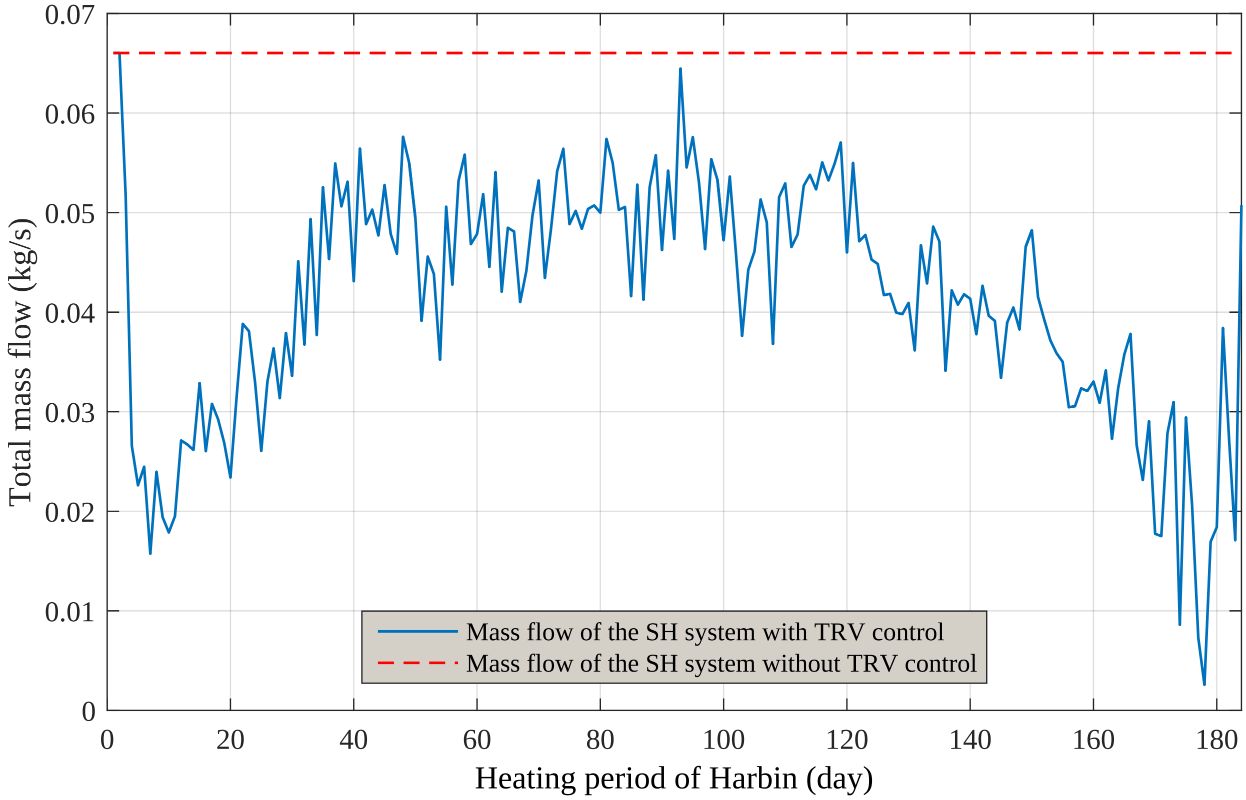


Figure 12. Heat consumption comparison between the scenarios with and without TRV control

Figure


0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Total mass flow (kg/s)
0
20
40
60
80
100
120
140
160
180
Heating period of Harbin (day)
Mass flow of the SH system with TRV control
Mass flow of the SH system without TRV control

Table

Table 1. Details of the relevant devices installed in tested apartment

Device name		Type	Dimension
Radiator valve		RA-N[21]	DN15 (mm)
Auto balancing valves	DP controller	ASV-PV[23]	DN20 (mm)
	Partner valve	ASV-M[23]	DN20 (mm)
Ultrasonic energy meter		SONOMETER 1100[24]	DN20 (mm)

Table

Table 2. Basic information about the apartment tested

Room name	Floor area (m^2)	Heat load (W)	Desired operating temperature difference (°C)	Desired flow (l/h)	Pre-set values
Living Room	18	810	15	46.4	3
Bedroom A	14.5	654	15	37.5	2.5
Bedroom B	8.7	391	15	22.5	1.5
Bathroom	3.4	168	15	9.6	1
Kitchen	4	180	15	10.3	1
Total	48.6	2203		126	

Table

Table 3. Temperature measurement comparison between with and without pre-setting in Test II

Parameter of tested apartment loop	No pre-setting	Pre-setting
Total flow of apartment loop (l/h)	557	181
Supply temperature (°C)	62.6	62
Return temperature (°C)	53.6	44.7
Delta T (°C)	9	17.3
Average indoor temperature (°C)	22.6	22
Outdoor temperature (°C)	-4	-4